NATO Advanced Research Workshop

on the Optics of Cosmic Dust

Program and Abstracts

Bratislava, November 16-19, 2001

Organized by

Astronomical Institute, Slovak Academy of Sciences
Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic

Army Research Laboratory
2800 Powder Mill Road, Adelphi, Maryland 20783-1197 USA

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The meeting will focus on recent advances in the scientific investigation of the interaction of electromagnetic radiation with dust particles, specifically cosmic. The aim is to bring together dust experts to discuss the current state of the art and to formulate new research directions. Bratislava's conference will cover aspects of the origin of cosmic dust particles, their chemical, and otical properties, structure, and shape, interaction of cosmic dust particles with electromagnetic radiation, and dynamics and applications to systems in the Universe.

The meeting take place at
Hotel Družba, Botanická street, 842 14 Bratislava, Slovak Republic

For further information see the conference home page http://astro.savba.sk/CDP2001

Program overview

Thursday, November 15

16:00-20:00 Preregistration in the reception of Družba Hotel

dinner 18:00-19:00

Friday, November 16

7:30-9:00 Registration
9:00-9:20 Conference opening

Opening Lecture, 9:20

- Dust and aggregates, G. Videen **(invited)**

SESSION 1: Origin of Cosmic Dust Particles, 10:00

- Grain evolution in space, Th. Henning **(invited)**

break 10:40-11:10

- Synchrotron FTIR examination of interplanetary dust particles and meteorites: An effort to determine the compounds and minerals in interstellar and circumstellar dust, G. Flynn, **(invited)**
- Radiation as a mean of mass segregation in meteoroid streams, *I. P. Williams*
- On fragmentation of meteoroids in interplanetary space, *V. Porubčan, J. Tóth*

lunch 12:30-14:00

***SESSION 2: Chemical, and Optical Properties, Structure, and Shape of Cosmic Dust Particles*, 14:00**

- Infrared spectroscopy of cosmic grains, Th. Henning **(invited)**
- Order-disorder in the dust and infrared spectroscopic properties, *J. R. Brucato*
- Optical properties of coated soot particles - Results of aerosol chamber experiments, *M. Schnaiter*
- The database of the optical properties of chaotically oriented fractal-like clusters of spherical particles, *S. A. Beletsky, V. P. Tishkovets, R. Waters, C. Dominik, P. V. Litvinov*

break 15:40-16:10

- Light scattering by cosmic dust: program codes, their pros and cons, and constraints imposed on the particles, *K. Lumme, K. Green* **(invited)**
- Fractal aggregates in space: their making and implications on polarization, *G. Wurm*
- Dust Opacities for Accretion Disks, *D. Semenov, Th. Henning, M. Ilgner, Ch. Helling, E. Sedlmayr*

- Photometric and polarimetric properties of glass spheres near opposition as seen with Kharkov's photopolarimeters, *A. A. Ovcharenko, Yu. G. Shkuratov* (POSTER)
- Reanalysis of porous chondritic cosmic dust particles, *I. Kapišinský, V. Figush, J. Ivan, K. Iždinský, M. Zemánková* (POSTER)

***General discussion to follow on presentations and their implications*, 17:30-18:00**

dinner 18:00-19:00
evening events 20:00-21:30

Saturday, November 17

***SESSION 3: Interaction of Cosmic Dust Particles with Electromagnetic Radiation*, 8:30**

- Kitchen of dust modelling, *N. V. Voshchinnikov* **(invited)**
- ..., *F. Gonzalez*
- Light scattering by large particles with random shape and applications to cometary dust and planetary regoliths., *Y. Grynko, D. Stankevich, Yu. Shkuratov*

break 9:50-10:20

- Scattering by complex particles - Recent advances using the microwave analogue method, *B. Å. S. Gustafson, L. Kolokolova, Y. l. Xu* **(invited)**
- Coherent backscattering by single inhomogeneous particles large compared to the wavelength, *K. Muinonen*
- The scattering, absorption and extinction efficiencies for hexagonal prisms, *A. G. Petrushin*
- Scattering by optically inhomogeneous spheres, *A. Y. Perelman, T. V. Zinov'eva*
- Calculation of optical fields inside the spheroidal particles of cosmic dust: comparison of different methods (GMT, T-matrix, SVM), *V. A. Babenko, P. K. Petrov*

lunch 12:30-14:00

- Thermal effect of radiation on dust particles, *L. G. Astafyeva*
- New light scattering tools to develop cosmic dust models, *D. N. Dubkova, V. B. Il'in, L. G. Astafyeva, V. A. Babenko, S. A. Beletsky, V. G. Farafonov, Th. Henning, P. V. Litvinov, A. Ya. Perelman, M. S. Prokopjeva, V. P. Tishkovets, N. V. Voshchinnikov, L. B. F. M. Waters, T. V. Zinov'ieva*
- Exact computations of coherent backscattering, *M. Mishchenko* **(invited)**
- Comparative study of coherent backscattering and shadowing mechanisms contribution in the formation of brightness and polarization opposition effects for different atmosphereless Solar-System bodies, *V. K. Rosenbush, V. V. Avramchuk, N. N. Kiselev*

break 15:40-16:10

- Simulation of the coherent opposition effects for discrete random media, *V. P. Tishkovets, P. V. Litvinov*

- Laboratory modeling of photometric and polarimetric opposition effects for cosmic dust and planetary regoliths, *Y. Shkuratov*
- Negative polarization of light scattered by cometary dust and planetary regoliths, *E. Zubko, Yu. Shkuratov*
- Some properties of polarization opposition effect. An application to Saturn's rings observations, *P. V. Litvinov, V. P. Tishkovets*

***General discussion to follow on presentations and their implications*, 17:30-18:00**
Conference dinner, 19:00-22:00

Sunday, November 18

***Interaction of Cosmic Dust Particles with Electromagnetic Radiation*, 8:30**
- Experimental determination of scattering matrices as functions of the scattering angle, *H. Volten, O. Muñoz, R. Waters, W. van der Zande, J. Hovenier*
- Scattering matrices of cometary analogues, *O. Muñoz, F. Moreno, A. Molina*
- Monte Carlo modelling of dusty cometary atmospheres including polarization, *F. Moreno, O. Muñoz, A. Molina*
- Polarimetric properties of the dust in disintegrating comets, *N. N. Kiselev, K. Jockers, V. K.* Rosenbush (POSTER)

break 9:50-10:20

- Ill-posed problems of light scattering for cometary dust, *M. Kocifaj, G. Videen, J. Klačka, F. Kundracík*
- Size distributions of particles obtained by inversion of spectral extinction and scattering measurements, J. *Olmo, L. A. Arboledas, H. Horvath, C. Sanchez, M. Gangl, O. Jovanovic, W. Kaller, H. Sauerzopf, S. Seidl*
- Size distribution of dust in comets Halley and Hale-Bopp, based on the thermal emission and albedo, *M. Šolc*
- Retrieval of the size distribution of magnetic spherules using the extinction data, *M. Kocifaj*
- Modelling of interstellar extinction with composite dust grains, *D. N. Dubkova, N. V. Voshchinnikov*

lunch 12:30-14:00

- The relation between extinction in the ultraviolet and the diffuse interstellar bands, *A. Megier, J. Krelowski, T. Weselak*
- Laboratory simulations of the interaction of interstellar carbon particles with UV photon and atomic hydrogen, *V. Mennella*
- Atmospheric extinction at the Skalnaté Pleso Observatory, *J. Svoreň, J. Žižňovský, Z. Mikulášek, J. Tremko* (POSTER)

***SESSION 4: Dynamics and Applications to Systems in the Universe*, 14:40**
- Radiation forces in the Discrete Dipole Approximation, *A. Hoekstra*
- Covariant equation of motion for arbitrarily shaped dust particle in the field of electromagnetic radiation, *J. Klačka* **(invited)**

break 15:40-16:10

- The capture of interstellar dust: electromagnetic radiation and Lorentz force, *J. Klačka*, *M. Kocifaj*

***General discussion to follow on presentations and their implications*, 16:30-17:30**

dinner 18:00-19:00
evening events 19:00-21:30

Monday, November 19

***Review of current knowledge and techniques*, 9:00**

break 10:00-10:30

***Roundtable discussion of what is needed in the field,* 10:30**

lunch 12:00-13:00

***Discussion of future research directions and formation of collaborative teams to focus on specific problems,* 13:00**

break 14:00-14:30

***Discussion of other applications,* 14:30**
All the sessions are planned to be small group discussions

ABSTRACTS

Dust and Aggregates

Gorden Videen

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Biological warfare (BW) agents are a prime concern to both military and civilian personnel because of both their lethality and the resulting terror they would inflict upon a population. Detecting and identifying aerosols is a primary objective of the US DoD and many other institutions worldwide. Light scattering may provide an automated means of rapidly detecting and identifying potentially lethal aerosols real-time without the use of chemical reagents or expensive maintenance. Since organic particles tend to fluoresce, many detector systems have focused on measuring this property to identify potentially harmful particles to raise an alarm. However, because fluorescence signals tend to be weak and smooth, it is difficult to differentiate among species of biological particles. Natural backgrounds vary widely and may cause false alarms. For this reason, other information is needed about the particle system that may be gathered from the elastic scattering spectrum.

One property of BW agents is that when they are aerosolized, they tend to aggregate into clusters. From the scattering signal, it might be possible to characterize the individual spores making up the cluster to help in the identification. However, again it is essential to be aware of the natural background signals caused by dust, diesel fumes, pollen, etc. and to develop methods to distinguish between these particles and the particles of concern.

SESSION 1

Origin of Cosmic Dust Particles

Grain Evolution in Space

Th. Henning

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Micron- and nanometer-sized solid particles play an important role in the evolutionary cycle of stars and the different phases of the interstellar medium. Primary dust particles form in the outflows of evolved stars and have a chemical composition, which reflects stellar evolution and physical conditions around the star. Grains are processed by shocks, UV light, and ion irradiation in the diffuse interstellar medium. In dense and cold molecular phases, ice mantles can form on the surface of the refractory cores and particles can start to coagulate and grow. This process is even more important in protoplanetary disks as the initial phase of planet formation. In this review the different evolutionary processes will be discussed.

Synchrotron FTIR Examination of Interplanetary Dust Particles and Meteorites: An Effort to Determine the Compounds and Minerals in Interstellar and Circumstellar Dust

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Much of what we know about the interstellar medium and about other stars comes from spectroscopy. Infrared spectroscopy generally provides identification of *solid compounds* and *minerals* in the dust. Recently, the Infrared Space Observatory (ISO) has greatly expanded the infrared spectroscopy of interstellar and circumstellar regions. Features are seen in emission in hot regions, or, in absorption in cold regions illuminated from behind by a continuum source. To associate a specific absorption feature with a particular compound or mineral the infrared signature of that compound or mineral must have been measured in the laboratory for comparison.

Interstellar grains occur in molecular clouds in interstellar space. These interstellar grains generally show broad 10 and 20 μm absorption features that suggest a disordered silicate. Interstellar grains also show several features near 3 μm consistent with C-H stretching vibrations in aliphatic hydrocarbon. Thus, the dominant type of interstellar grain is thought to be a glassy silicate coated with organic matter. *Circumstellar grains* occur in clouds surrounding other stars. A variety of grains, including crystalline silicate, glassy silicate, oxides, and other phases, many yet unidentified, occur in the circumstellar environment.

Since the mid-1970s NASA has recovered interplanetary dust particles (IDPs), fragments from comets and asteroids, from the Earth's stratosphere. These small ($\sim$5 to 25 μm) IDPs decelerate from interplanetary velocity (>11 km/sec) in the Earth's upper atmosphere, generally without significant heating. These particles are similar in composition and mineralogy to primitive meteorites, but many IDPs have high volatile element contents, very unequilibrated mineralogies, and spots of high D/H. Many of the IDPs are very primitive, having experienced minimal thermal and aqueous alteration. Thus they are good candidates for the preservation of interstellar grains.

We have begun a comprehensive project to characterize the components of IDPs, meteorites and terrestrial minerals, in an effort to identify the compounds and minerals in interstellar and circumstellar grains. The IDPs, which are believed to be fragments of comets and asteroids, consist of micron to sub-micron aggregates of different minerals and compounds. Because of the small size of these individual subunits, the high intensity of synchrotron-based FTIR is required to obtain spectra of the subunits of the IDPs.

Bradley [1] suggested that $\sim$0.5 μm glass subunits, containing nanometer size Fe-Ni-metal and Fe-sulfides, which he called GEMS, found in IDPs were good candidates for interstellar silicate. We measured the FTIR spectra of subunits of an $\sim$12$\times$8 μm fragment from an IDP, L2011*B6, that is dominated by Fe-sulfide (pyrrhotite), but includes two GEMS-rich lobes, and carbonaceous material (maybe organic) associated with GEMS. The GEMS in L2011*B6 are an excellent match to the 10 μm interstellar dust feature [2], and the 18 μm feature of the GEMS is also a good match to the interstellar feature. *This is the first time any single, naturally occuring material has matched the interstellar 10 and 18 μm features.*

In ISO spectra of some cold, dense molecular clouds and around some evolved stars, there is an excess flux between 20 μm and 26 μm, which was attributed to FeO based on calculated spectra derived from experimentally determined optical constants combined with theoretically modeled grain shapes. We measured the FTIR spectra of wüstite (FeO) and another Fe-oxide (magnetite) both of which have a strong feature at $\sim$ 17.5 μm, not seen in the ISO spectra. *This excludes wüstite and magnetite as source of the 23.5 μm feature.* We measured the infrared spectra of an

Fe-sulfide standard (pyrrhotite) and Fe-sulfides in two IDPs. The pyrrhotite standard is an excellent match to the ISO feature, *suggesting that pyrrhotite is a previously unrecognized interstellar and circumstellar grain.*

We measured C-H stretching vibrations, which occur in the 2800 to 3000 cm^{-1} range, in the IDPs. These features have previously been detected in interstellar grains. The ratio of the $C\text{-}H_2$ to the $C\text{-}H_3$ absorption features is a measure of the length of the aliphatic molecule. The more intense $C\text{-}H_3$ absorption, relative to $C\text{-}H_2$, in the interstellar feature *indicates that the aliphatic chain is shorter in the interstellar material than in the interplanetary dust.*

References

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Radiation as a Means of Mass Segregation in Meteoroid Streams

I. P. Williams

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It is well-known that the effect of radiation on meteoroids is size dependent, the effect being generally inversely proportional to radius. It is also well-known that the Poynting-Robertson drag reduces both semi-major axis and eccentricity. In interplanetary space it is thus obvious that mass segregation takes place within streams with the smaller meteoroids tending in time to move on smaller more circular orbits. However, whether or not meteoroids are actually observed as meteors depends only on the position of the orbital nodes, that is, Ω and r_N. We will discuss the effects of radiation on these two parameters in order to establish the importance of radiation in the evolution of the observed component of a meteoroid stream.

On a Fragmentation of Meteoroids in Interplanetary Space

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A possible fragmentation of meteoroids in interplanetary space inferred from grouping of particles in meteor streams is discussed. There is a conviction maintained by many observers that meteors within the streams are observed to be clustered in pairs or larger groups more frequently than one could expect from chance distribution. The rate of dispersive effects indicates that the lifetime of any such a group of meteoroids is very limited. Therefore, if real, the pairs or groups must be due to recent fragmentation of larger meteoroids.

Analyses based on visual observations of meteor streams lead to contradictory results with some in favour of a non-random grouping of meteors for the Perseids and Leonids. Much more conclusive are analyses based on radio measurements, which present a definitive negative result concerning the permanent meteor showers with the stream structures at their middle and late evolutionary stages, and an indication of a positive result for younger dense stream structures of recent origin. Analysis of the 1969 Leonid display obtained by the Springhill high-power radar shows that about 10 % of the population around the shower maximum is associated in close groups. The recent Leonid returns with the storm in 1999 provided a possibility to verify a non-random grouping of particles within this young filament of the stream. The analysis and results based on TV observations of the Leonid storm in 1999 are presented and discussed.

SESSION 2

Chemical, and Optical Properties, Structure, and Shape of Cosmic Dust Particle

Infrared Spectroscopy of Cosmic Grains

Th. Henning

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The optical properties of cosmic grains determine the interaction of radiation fields with this kind of matter, thereby influencing the temperature and spectral appearance of dusty regions and the radiation pressure exerted on the gas.

The talk will deal with the relevant optical data for interstellar, circumstellar, and protoplanetary grains. These data can be obtained by laboratory measurements on material collected in situ in the solar system or by measurements on cosmic dust analogs. This review will concentrate on the production, analytic characterization, and optical data of cosmic dust analogs. The necessary basic knowledge, how such data can be measured in the laboratory and how they have to be used for astrophysical applications, will be provided.

Order-Disorder in the Dust and Infrared Spectroscopic Properties

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Since their formation in the outflows of evolved stars, materials suffer in space deep chemical and physical modifications. Most abundant elements (C, N, O, Mg, Si, S and Fe) are present in dust grains as various refractory chemical species. Among them silicates are one of the main constituent. Spectroscopical observations of various astronomical environments have shown that magnesium rich silicates are present both in amorphous and in crystalline phase. An accurate interpretation of these observations requires studies on the formation of silicate dust in the atmosphere of giant stars and their evolution in the interstellar medium until their inclusion in the protoplanetary disks.

Musch theoretical work was devoted to describe the chemical and physical evolutions of solids in space and their link to the optical observable properties. To improve the development of models, studies in laboratory of cosmic dust analogues are necessary.

In this work laboratory experiments aiming to simulate the formation and the structural evolution of silicates in space are presented. In particular laser evaporation technique is used producing amorphous silicates with various Si-Mg-Fe content. Analyses of the evolution of structure amorphous-crystal of silicates by thermal annealing is ivestigated by infrared spectroscopy. Laboratory and space physical conditions are discussed.

Optical Properties of Coated Soot Particles - Results of Aerosol Chamber Experiments

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Soot is a major component of interstellar dust which is reflected by the ubiquitous 217.5 nm absorption band in interstellar extinction. Due to its strong absorption efficiency in the ultraviolet and visible spectral region soot plays an important role for the heating balance of interstellar clouds. In the Earth's atmosphere anthropogenic soot is by far the main absorbing aerosol component for visible solar radiation and, thus, may influence local and global climate significantly [1]. Whereas interstellar soot is formed in the expanding outflows of carbon-rich asymptotic giant branch (AGB) stars, atmospheric soot is emitted by human activities like fossil fuel and biomass burning. In both environments the freshly emitted soot particles are aged by microphysical processes like coagulation and particle coating by condensation of low volatile compounds (e.g. water, organics). A lot of experimental work were done to understand the link between the solid state structure of soot and its optical properties (e.g. [2]). Much less experimental investigations were done to assess the influence of interstellar and atmospheric aging processes on the soot optical properties [3].

The large aerosol chamber facility AIDA of the Forschungszentrum Karlsruhe is well suited to simulate atmospheric aerosol aging processes over a wide range of temperature and pressure conditions. The chamber is equipped with two home-made extinction cells measuring *ex situ* the aerosol extinction coefficient spectrally resolved from the mid-UV to the near-IR (200 to 1000 nm). The aerosol scattering coefficient is measured simultaneously at 450, 550, and 700 nm by means of a commercial integrating Nephelometer providing the single scattering albedo, the absorption coefficient, and the hemispheric backscatter ratio. A spark discharge generator and a commercial Diesel engine are available soot sources. Organic particle coating is achieved by the ozonolysis of a-pinene in the presence of soot in the chamber.

Pure coagulation experiments with soot aerosol were carried out in the chamber over time scales of days, resulting in a coagulation-induced aggregate growth from 1000 to 100000 monomers per aggregate in case of spark discharge soot. Almost no change in spectral soot extinction and scattering behavior with time was found for the coagulation aging in this aggregate size range. The coating of soot with dielectric organic material led to a dramatic change of the aerosol scattering properties and to a significant increase of the soot absorption cross section. The results are discussed in terms of core - mantle particle formation as well as aggregate restructuring.

References

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Database of the Optical Properties of Chaotically Oriented Fractal-like Clusters of Spherical Particles

[1]S. A. Beletsky, V. P. [1]Tishkovets, R. [2]Waters, C. [2]Dominik, and [3]P. V. Litvinov

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Interpretation of remote sensing observations of cometary and interplanetary dust requires understanding the light interaction with small particles, which depends on such parameters as shape, size and composition of the particles. To reduce number of the parameters and simplify calculation procedures the model of spherical particles is often used. Theory of light scattering by spherical particles allows calculating the characteristics of scattered radiation for particles of any size and composition. But cometary and interplanetary dust most probably seemed be the aggregates (clusters) of small particles [1]. The optical properties of such compound particles appreciably differ from those of isolated particles. In particular, the photometric and polarimetric opposition effects cannot be properly explained within the theory of light scattering by a single particle whereas both effects are typical for cluster of particles (see, for example, [2]). But for calculation the cluster scattering characteristics more parameters must be taken into account than for isolated scatterers. The additional parameters are the number of particles in the cluster and the parameters describing the cluster structure. At present time the procedure of calculation of scattering matrix is well developed both for oriented clusters of spherical particles and for chaotically oriented one [3]. To reduce number of input parameters the cluster constituent spheres are usually chosen identical to each other and structure of the cluster is considered to be fractal-like. The structure properties of fractal-like cluster consisting of a great number of particles can be characterized by two parameters only [4]. These are fractal dimension D and a prefactor constant ρ. Such aggregates have structure that can be presented by $N = \rho(R_g/2a)^D$, where N is number of constituent spherical particles of the cluster, a is the radius of the particle, R_g is the radius of gyration of the cluster. However, the numerical calculation of scattering matrix for such a kind of scatterers takes a lot of computer time even at moderate numbers of constituent spheres. Therefore, for interpretation of different kind of observations of cometary and interplanetary dust is necessary a detailed database of optical properties of such particles with quickly interpolation of optical properties over all parameters of clusters. For creation the database we use a model of the artificial neural network called the layered perceptron (see, for example, [5]). The perceptron can be defined as a connected array of elementary processors called neurons. We use the model of the perceptron consisting of six input neurons, thirty output neurons and two hidden layers with thirty neurons in each one. The number of input neurons corresponds to number of parameters defining of the cluster properties: $x, Re(m), Im(m), D, \rho, N$. Here $x = 2\pi a/\lambda$ is the size parameter (λ is the wavelength of incident radiation), $Re(m)$ and $Im(m)$ are the real and imaginary part of the complex refractive index. The output perceptron data are the expansion coefficients of the scattering matrix elements in series of the generalized spherical functions. The data for perceptron training was obtained using D. Mackowsky and M. Mishchenko code [3]. About two hundred points for the input parameters in range of $x = 1.5$; $1.4 \leq Re(m) \leq 1.7$; $0.001 \leq Im(m) \leq 0.1$; $D = 3$; $\rho = 8$; $N \leq 50$ was used for training the perceptron. During training process the perceptron is defining and memorizing a hypersurface in space of input-output parameters that in the best way corresponds to the data set presented for training. The trained perceptron allows calculating the approximate values of the expansion coefficients for any input data from the data range that was used for neural network training. Errors in output parameters depend, in particular, on perceptron structure and training

time. At present time the perceptron can calculate the expansion coefficients of S_{11} and S_{21} matrix elements. The maximum error for S_{11} matrix element was found to be less then 15%.

An example of perceptron calculation of linear polarization degree for $x = 1.5$; $N = 20$; $Re(m) = 1.7$; $Im(m) = 0.08$ is presented on Fig.1. These cluster parameters were not used for perceptron training.

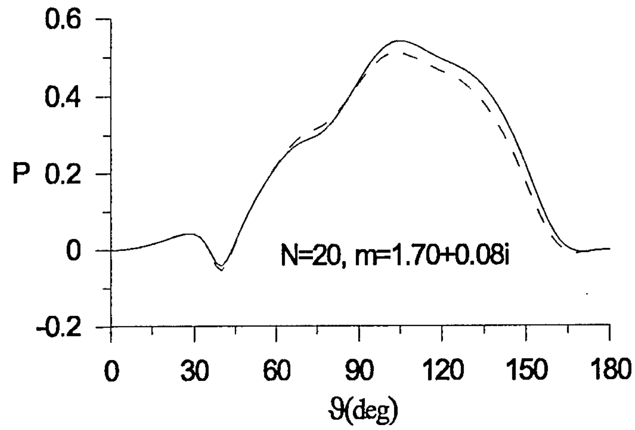

Figure 1: Linear polarization degree P vs scattering angle ϑ. Solid curve corresponds to the accurate values, dotted line corresponds to values calculated by the perceptron.

Advantages of the database are the small size and quick data access. Moreover there is a possibility to extend and make the database more exact without an increasing data time access and size of the database. In future we plan to extend the database for other value of D, ρ, N.

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Light Scattering by Cosmic Dust: Program Codes, Their Pros and Cons, and Constraints Imposed on the Particles

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Cosmic dust in the form of irregular solids or stochastic aggregates nearly permeates our solar system. These dust particles can be found on the surfaces of atmosphereless bodies, in the interplanetary space, and in the cometary comae. Learning more about this dust should obviously provide valuable insights into the formation of the solar system.

Aiming at studying the composition of cosmic dust, light scattering and electromagnetic interactions such as the Poyting–Robertson effect / radiation pressure play essential roles. Both of these are sensitive to such material parameters as the real and imaginary parts of the refractive index and morphological parameters including the size distribution and, of course, general geometry, determining whether we are dealing with a solid or an aggregate.

Our planetary group at the Observatory of the University of Helsinki has during the past few years been collecting, improving, and creating new computer codes suitable for undertaking both light scattering and radiative transfer calculations involving cosmic dust in various environments. Interestingly enough, the same program codes have also found wide applications in such mundane areas as paper, paint, and pigment industries, the last-mentioned of which we are actively participating in. In these applications the pigments play the role of cosmic dust particles.

The main computer codes which we are currently using, inter-comparing, and further developing are based on the discretization of the volume integral equation (VIE) for scattering, on the T-matrix method with the computational formulations mainly written by Mishchenko, and on sphere-cluster formulations. For complicated non-symmetric particle geometries our code based on the VIE is the only possibility at the moment. Unfortunately, in the case of modelling the polarization of cosmic dust observations that code is not very accurate in the backscattering direction. As is well known, the codes based on the T-matrix method are very accurate and fast, but they are all suffering from rather unpredictable convergence. We are currently attacking the convergence problem by trying different numerical quadrature forms for the integration over the particle surface. To our best knowledge all the existing T-matrix codes employ the standard Gauss–Legendre quadrature for the integration. Our preliminary results seem to indicate that the Gauss–Chebyshev quadrature results in a more stabilized convergence.

Closely related to the light scattering problems is the question how to model the shapes of cosmic dust particles. We have created various algorithms to stochastically deform a basic shape such as a sphere, spheroid, or a cylinder. We have also written codes to close-pack non-spherical constituents in an aggregate with touching neighbors (up to packing densities of the order of 0.5). We are systematically mapping the light scattering properties of different particle types and also trying some inverse methods, i.e., to infer particle properties from measured light scattering data.

Our astronomical goal in the light scattering project is to understand the composition of dust in the solar system. Following our previous activities in the field of light scattering by planetary regoliths and interplanetary dust we are working on the multiwavelength polarization data of various groups of comets. So far we have been able to fit the data for comets with high maximum polarization and comet Hale-Bopp with a model of highly elongated cylinders (L/D $\sim$ 3) with an average size of about 0.5 μm. In spite of the formally good fits we have to be somewhat worried about the uniqueness of those fits. The ubiquitous feature in almost all data obtained from the atmosphereless bodies of the solar system is the so-called negative polarization with the inversion solar phase at

about 20°, and, unfortunately, most model particles seem to require a very precise fine-tuning for the particle size to produce the same angle for the inversion of polarization. On the other hand, we are fairly confident of the required size distribution for the cometary particles. All the existing polarization data indicate that the inversion of polarization is independent of the wavelength, and it is quite straightforward to show that this can only happen if the particle size statistics follows a power law.

Fractal Aggregates in Space: Their Making and Implications on Polarization

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Extinction and polarization by cosmic dust particles is a major source of information about those particles and the regions in which they are embedded. It is widely accepted that e.g. the interstellar dust particles have to be elongated and aligned to produce polarization by dichroic extinction.

Models built on simple non-spherical particle shapes (ellipsoids, cylinders) can formally (and very well) be fitted to observed features of extinction and polarization in the general diffuse interstellar medium [1]. However, no self consistent explanation has been given yet to explain the differences in extinction and polarization, e.g. systematic correlated deviations from the average or differences which occur in denser regions or in molecular clouds at higher galactic latitude. It is inevitable that 'simple-shaped' models have to fail to explain changing features by simple means, e.g. by only changing the overall size, if dust particles aggregate – a process which is widely accepted to take place already in interstellar regions [2] and which is rather certain to represent the onset of planet formation in young circumstellar disks [3]. This paper will report on experimental findings, suggesting that fractal aggregates built in a cluster cluster aggregation (CCA) process are likely to be present in all regions where particles ever collide and stick, i.e. in protoplanetary disks and in the interstellar medium.

Particles will be assembled in a random orientation if they aggregate, regardless of any initial shape. Therefore, individual shapes can no longer be responsible for polarization. If aggregates of different size are modeled by those simpler shapes all the same, there have to be different assumptions for the properties of the particles, e.g. as changing the mantle thickness of core mantle particles [4]. This might induce questions and ideas on why those different properties arise. However, if aggregates are treated as aggregates, the aggregate size might be the only parameter that needs to be adjusted without the need to change the properties and therefore history of the individual constituents. If dust particles are aggregates any major feature in polarization has to arise from the aggregate morphology anyway.

This paper shows that indeed all major correlations of features in interstellar extinction and polarization can well be explained by aggregates of different size. This includes molecular clouds in high galactic latitude and the linear correlation between total to selective extinction and the wavelength of maximum polarization. It will present calculations based on the code by D. Mackowski, K. Fuller, and M. Mishchenko which is publicly available (thank you for the code!).

The calculations also show that aggregate growth leads to a systematic decrease in the maximum degree of polarization as seen in fig. 1. This puts a restrictive upper limit on the aggregate size if polarization is observed.

It will further be discussed which implications these results, i.e. applied to observations of polarization and extinction, suggest for aggregate sizes and growth, dust densities or timescales for the observed states of interstellar matter (e.g. dark clouds) by means of a simple coagulatoin model. Characteristic coagulation timescales on which two particles collide on average and form a particle twice the mass can be estimated by

$$\tau = \frac{1}{n \cdot \sigma \cdot v}, \qquad (1)$$

with n being the particle number density, σ being the collision cross section, and v being the collision velocity. A very small degree of aggregation which has to be assumed consistently with the

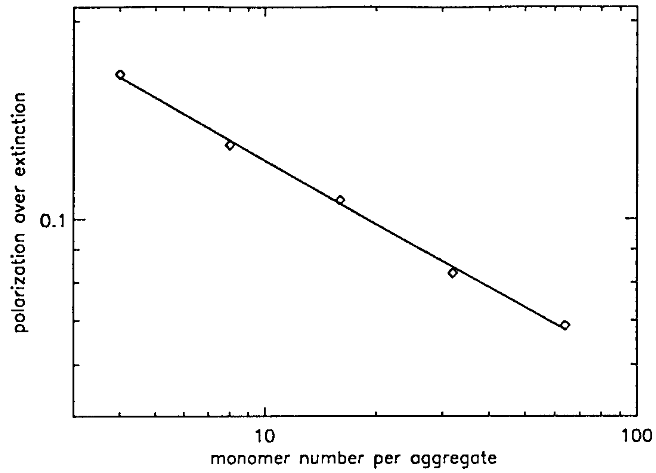

Figure 1: Maximum polarization over aggregate size in monomer numbers. Polarization over extinction is defined by the difference in extinction efficiencies for polarizations along the small and long aggregate axis divided by the sum. The maximum polarization is essentially independent of the monomer size but as can be seen it strongly depends on the monomer number per aggregate. Therefore, small but only small aggregates are able to provide a sufficient amount of polarization.

observation of polarization and extinction e.g. in parts of the Taurus Dark Clouds which are less dense suggests that the conditions met approximately values to match one coagulation timescale τ with the age of those parts of the clouds. Assuming e.g. an H_2 density of $10^4/\mathrm{cm}^{-3}$, a dust to gas mass ratio of 0.01, an average particle of of 100 nm radius, and (turbulent) collision velocities of (a few) m/s, τ would be on the order of 10^6 years, though there is some uncertainty in all of the quantities mentioned. This would match the timescale on which the Taurus Cloud has formed stars [5]. However, together with a more detailed analysis of the coagulation process, polarization and extinction analysis might offer independent means of determining these parameters. In combination with other observations this might aid to decrease the uncertainties for some values (e.g. cloud life times or collision velocities). Regarding particles as aggregates rather than just particles of some elongated shape might thus have further advantages than just providing one more way to match interstellar polarization and extinction.

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Dust Opacities for Accretion Disks

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The growing knowledge about dust grains and gas species in different astrophysical objects during recent years allows the consideration of more realistic opacity models in large-scale hydrodynamical calculations for protoplanetary disks. We developed[1] such a new model based on the unification of the refined dust models proposed by Pollack et al. [1], Henning & Stognienko [2] with the gas model of Helling [3]. The following assumptions and approximations were used:

1) LTE, local thermal equilibrium of a medium;

2) In regions where dust grains can exist, it is supposed that they are the main source of the opacity, otherwise the opacity dominated by atoms, ions and molecules has to be applied;

3) The major dust species include olivine ($[\mathrm{Fe,Mg}]_2\mathrm{SiO}_4$), orthopyroxene ($[\mathrm{Fe,Mg}]\mathrm{SiO}_3$), volatile and refractory organics, water ice, troilite (FeS), and metallic iron;

4) The fractional abundance of each dust component is approximated by constant values within the temperature interval where it can exist and is constrained by solar elemental abundances [4] and chemical models;

5) The sublimation temperatures of grains are computed by chemical equilibrium calculations with a limited number of chemical species and taken to be dependent on the gas density;

6) For the size distribution a modified MRN function is assumed:
$n(r) = 1,\ r < 0.005\mu\mathrm{m} = \mathrm{r}_0,$
$n(r) = (r_0/r)^{3.5},\ r_0 \leq r < 1\mu\mathrm{m},$
$n(r) = (r_0)^{-2}(r_0/r)^{5.5},\ 1\mu\mathrm{m} \leq \mathrm{r} < 5\mu\mathrm{m},$
$n(r) = 0,\ r \geq 5\mu\mathrm{m}$, where r is a particle size;

7) The grains are considered to be in a form of chemically homogeneous spherical or aggregate dust or inhomogeneous (composite) aggregates (50% BPCA and 50% BCCA);

8) The major gas species include CO, TiO, SiO, H_2O, CH, CN, C_2, C_3, HCN, C_2H_2, CO_2, O_2, N_2O, CH_4, O_3, NO, SO_2, NO_2, NH_3, HNO_3, OH, H_2CO, N_2, H_2S, HO_2 (absorption lines), HI, H^-, H+H, H_2^-, H_2^+, HeI, He^-, CI, MgI, AlI, SiI (continuum absorption), HI and HeI (Rayleigh scattering) and e^- (Thompson scattering);

The Rosseland and Planck mean opacities were computed for gas densities between 2×10^{-18} g cm^{-3} and 2×10^{-7} g cm^{-3} and temperatures between 10 K and 10,000 K. As an example, results of our calculations of Rosseland mean for different types of silicate dust in comparison with the opacity models proposed by Alexander & Ferguson (1994, [5]), Bell and Lin (1994, [6]), and Bell et al. (1997, [7]) are shown in Figure 1. The higher values of the dust opacity produced by our opacity model in comparison with the others can be explained by the joint effects of less compact particles, new optical constants and a more accurate compositional model we have used.

[1]For more details visit: http://www.astro.uni-jena.de/Users/henning/Opacities/opacities.html

Additionally, we investigated the influence of the Rosseland mean opacities computed by two rather different opacity models on the hydrodynamical structure of an active steady-state accretion disk. From Figures 2 and 3 it can be clearly seen that the higher values of the Rosseland mean dust opacity in case of our model cause a hotter disk structure and a more extended, less dense and flared atmosphere than by Bell's model. Thus hydrodynamical simulations of such disks must incorporate the best available state-of-the-art opacity models to produce a reliable physical description of their evolution.

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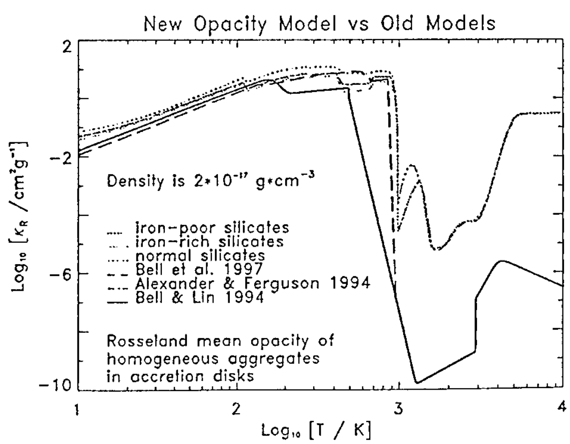

Figure 1: The Rosseland mean opacities calculated by our model for three types of silicate dust (homogeneous aggregates) in comparison with the models by Bell & Lin (1994), Bell et al. (1997) and Alexander & Ferguson (1994).

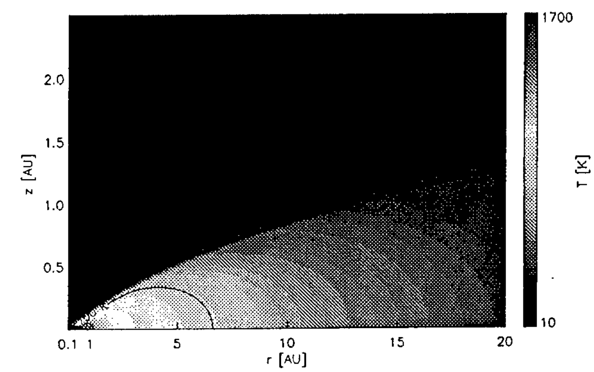

Figure 2: The structure of the protoplanetary disk derived with the opacity model of Bell & Lin (1994).

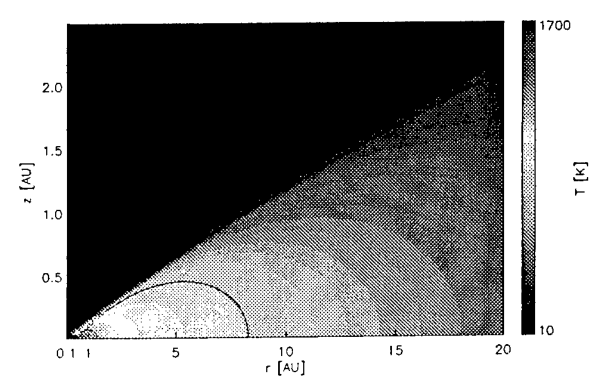

Figure 3: The structure of the protoplanetary disk calculated for our opacity model in the case of chemically homogeneous dust aggregates ("iron-poor" silicates).

Photometric and Polarimetric Properties of Glass Spheres Near Opposition as Seen With Kharkov's Photopolarimeters

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After modernization, two laboratory instruments for investigation of photometric and polarimetric properties of powdered surfaces, levitated layers, and suspensions are used at Kharkov Astronomical observatory. One of them allows measurements at the range of phase angles 0.2-12 degrees. The other one covers the range 1-177 degrees. In both cases unpolarized light sources (filament lamps) are utilized, though for some measurements we are able to measure linearly polarized light sources. Both our instruments have the same spectral bands that allows mutual comparison and merging data files. We use usually bands centered at 0.63 and 0.45 microns. The angular diameters of the source and receiver apertures are 0.05 and 0.8 degrees for small-phase-angle and large-phase-angles instruments, respectively. The first photopolarimeter deals with samples covering an area of 80 mm in diameter. The second one uses smaller samples with a diameter near 20 mm. More information about the instrument can be found, e.g., in [1].

The instruments have enabled us measurements of many samples with different structure and composition. For example, we extensively studied photometric and polarimetric properties of rather perfect glass spheres (with diameters 30-80 micron) near opposition. Spherical particles can be present at cosmic dust and planetary regoliths as they are a product of impact events. We investigated monolayers (on a very dark background) and thick slabs of transparent beads. The samples of glass spheres showed very prominent features related with the glory and rainbow rings. These features are clearly seen for monolayers as well as thick slabs. For example, a positive polarization spike near 1 degree related with a glory ring is found. It can be used as an indicator of spherical particle presence in light scattering objects.

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Reanalysis of Porous Chondritic Cosmic Dust Particles

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The particles reanalysed in this study were obtained from the NASA Johnson Space Center (JSC) Cosmic Dust Collection. The reanalysis of the particle L2008 P9 indicates typical assemblage of olivine - pyroxene. This sample can be classified as a chondritic porous IDP with the metallic phase grain containing essential amount of nickel and copper (the latter element is most probably due to instrumental artefact). The chemical composition of the particle L2011 S5 corresponds mostly to an assemblage of pyroxene phase - $(Mg,Fe,Ni)SiO_3$ roughly 75 wt.% and a sulphide phase - probably pyrrhotite (Fe,Ni)S about 25 wt.%.

SESSION 3

Interaction of Cosmic Dust Particles with Electromagnetic Radiation

Kitchen of Dust Modelling

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Dust grains were detected in almost all astronomical objects from local Earth's environment to very distant galaxies. The characteristics of dust vary significantly from one object to another, but the interaction of radiation with grains ia always described by the theory of light scattering by small particles. In general, it is possible to observe the processes of 1) *extinction*, 2) *scattering* and 3) *emission* of radiation by cosmic dust.

Interpretation of observations of dusty objects (*"kitchen of dust modelling"*) includes three components.

1. Establishment of the elements which can be converted into the solid state in the circumstellar/interstellar conditions, the determination of the resulting *materials* and then the measurements or finding of the *optical constants* (refractive indices) of materials under consideration.

2. Selection of the *light scattering theory* which has to give the possibility to represent the most significant features of the observational phenomenon and to work rather fast in order to give results in reasonable time.

3. Proper choice of the *object model* which includes, in particular, the correct treatment of the radiative transfer effects.

The current state of the components of dust modelling are discussed. Some conclusions on what information about the cosmic dust is reliable and what may be false are given.

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Light Scattering by Large Particles with Random Shape and Applications to Cometary Dust and Planetary Regoliths.

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Both cometary dust and planetary regolith are believed to consist basically of small closely-packed particles with typical dimensions of a few microns to tens of microns. However, a portion of the dust and regolith can be presented by large particles. Therefore, the geometric optics approximation can be used effectively to study scattering characteristics of the cosmic matter. In particular, the computer simulation as a method to investigate scattering properties of particles with arbitrary shape can be very effective [1], [2], [3], [4].

In our geometric optics model particles are homogeneous and isotropic and represented as a succession of triangular facets attached to each other, so that one can put a normal to every facet and calculate all necessary angles relative to the normal [1]. While rays are traced four Stokes parameters are attributed to each ray. At a boundary, surface reflection and refraction take place according to Snell's law and Fresnel's formulas. When a ray intersects a facet, the result can be described by two new rays: reflected and transmitted ones. Fresnel's formulae give the intensity for each of these two new rays. We use the ray intensities as probabilities, and according to these probabilities, we choose randomly among the two and track one of them. Instead of attenuating of the intensities of our rays according to Bouger law, we calculate the absorption probability of the ray path length and decide whether the ray has been absorbed. During the entire time of ray tracing a particle is randomly rotating around various axes, so we average result over all particle orientations. To calculate the phase curve, the space from 0 to 180 degrees is divided into a number of angular bins and the Stokes parameters of rays scattered into each bin are summed. Besides, our model allows to consider separately the contributions of different scattering orders tracking the information about the number of reflections and transmissions and to find out which order is responsible for a given feature in the scattering properties of a particle.

The main properties of a particle are its composition, size and shape. In this paper we consider the influence of refractive index, shape parameter and absorption ability on the behavior of intensity and polarization phase curves. The real part of the refractive index of the particle substance is taken into account to calculate refraction and reflection (the refractive index of the surrounding medium is taken to be unity). The very small imaginary part assumed here has a negligible influence on refraction and reflection, but it becomes efficient for large particles where rays have great path lengths. Decreasing the refractive index n produces more forward scattering and more negative polarization at phase angles > 130 degrees. At higher n, scattered light at all phase angles becomes positively polarized. To characterize particle shape we found a centroid for a particle, then put a vector from the centroid to each facet calculating the angle between this vector and the normal to the facet. The average angle over all facets of the particle is directly connected with particle shape: it is equal to zero in the case of sphere and aspires to 90 deg. for a fluffy particle. When increasing roughness rainbows and other features spread and disappear, forward scattering diminishes; positive and negative polarization branches gradually become weak. Effect of absorption is also important. At increasing of this parameter, forward scattering diminishes and polarization degree at large phase angle grows as it is predicted by Umov's law.

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Light Scattering and Absorption by Aggregates Based on Microwave Analog Experiments and Theory

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We report on a survey of light scattering characteristics of aggregated particles of physical characteristics selected to be representative of interplanetary dust including cometary dust and asteroid fragments using the parameterized models by Gustafson et al. [1]. The study is in part based on the microwave-analog-to-light-scattering facility at the University of Florida [2] and in part on theoretical modeling using computer codes [3]. The results were analyzed using multifactor analysis to parameterize the dependency of scattering properties on physical properties [4].

Aggregates of a variety of physical characteristics (number and size of constituent particles, packing factor) were used in the investigation and the scattering was obtained at a variety of orientations (to simulate single and random orientations) and across a range of wavelengths (to study spectral properties). In studying the spectral properties, we have separated geometric effects from the material properties, i.e., refractive index. To satisfy the requirements of the statistical multifactor analysis, known as 2^k factorial design, each of three characteristics of an aggregate (number, particle size, and aggregate packing factor) could take two fixed values. In each new experiment only one characteristic differed from those in the previous experiments. Thus, eight (2^3) aggregates of all possible combinations of two values of three parameters were studied. The values of the characteristics were: 1000 and 5000 for the number of particles in the aggregates; the particle size corresponded to 0.25 and 0.5 micron; the packing factor (the ratio of the total volume of the particles to the volume of the aggregate) was 10 and 50%. The angular and spectral dependencies of intensity and polarization were obtained for these aggregates. The subjects of the statistical analysis were: color, polarization and polarimetric color around the scattering angle 90 degree.

The statistical analysis shows that the intensity and polarization are mostly affected by the size of the constituent particles. The size also determines the shape of the angular and spectral dependencies and, consequently, the color and polarimetric color. The packing factor and number of the particles have less influence on the light-scattering characteristics within the range studied. This is in agreement with earlier studies summarized by Gustafson et al. [1] but extends the range of these studies.

Based on these findings we draw tentative conclusions about the possible physical properties of interplanetary dust and find that aggregates at about 10% packing of dust grains resembling classical size interstellar grains is a good representation. The dust parameters are similar to that expected based on the "Bird's-nest" model originally proposed by Greenberg and Gustafson in 1981 [5].

Adopting, the model found above, we present initial results on the energy deposition in interplanetary dust aggregates through absorption and find that the energy is not uniformly absorbed throughout the aggregates. Assuming that interparticle conductivity is negligible at the packing factor of 10%, the resulting temperature gradients and distribution throughout an aggregate of 10^4 particles is calculated based on radiative transfer. For the radiative cooling, the aggregate is treated as a single particle with the refractive index given by effective medium theory at the infrared

wavelengths that dominate cooling. The aim with these calculations is to show the extent to which volatiles can survive inside aggregated interplanetary dust grains.

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Coherent Backscattering by Single Inhomogeneous Particles Large Compared to the Wavelength

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A modified geometric optics approximation is outlined for small inhomogeneous cosmic particles large compared to the wavelength. Fresnel reflection and refraction are taken into account according to the well-known geometric optics approximation. In addition, coherent backscattering contributions are computed for internal particle inhomogeneities. Preliminary results are here provided for light scattering by convex opaque particles large compared to the wavelength. The results compare successfully with some recent experimental measurements.

The Scattering, Absorption and Extinction Efficiencies for Hexagonal Prisms

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The expressions for the calculations of scattering Ks , absorption Ka and extinction Ke efficiencies at the sizes of hexagonal prism commensurable with the incident radiation wavelength were obtained. The prism may have definite orientation relatively to the direction of incident radiation propagation. The expressions for Ke and Ka efficiencies for the soft particles were improved with the account for the radiation on a particle (a hexagonal prism) surface on which not only a phase shift of the refracted radiation relatively to the radiation phase occurred but also a certain decrease of the electric field vector amplitude took place for the radiation that went in a forward direction from the prism that underwent several refraction events. This is the next approximation as compared with [1], where expressions for calculations of the efficiency factors for optically soft hexagonal prisms were obtained. The scattering, extinction and absorption efficiencies for a single prism were later on approximated over the prism rotation angle relatively to its main axis , then an approximation was made over a possible prism orientation relatively to the direction of incident radiation propagation characterized by the angle . The Ks , Ka and Ke in case of a prism orientation in some chosen plane [2] may be determined by the method given in [3].

The accuracy of the obtained expressions was estimated by comparing our calculation results for the extinction factors for ice hexagonal prisms with similar data obtained by other authors [4] and with the experimental data on the extinction efficiency for ice crystals [2] . The error of our results appeared less than that in similar results obtained under the approximation of particles optical softness.

The scattering Ks and extinction Ke efficiencies of ice hexagonal prisms for some wavelengths of the incident radiation were calculated with the use of the obtained approximated expressions.

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Scattering by Optically Inhomogeneous Spheres

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The method to construct the components of the electric and magnetic vectors and different optical characteristics in the problem of light scattering by spheres with radially variable refractive index has been proposed [1], [2]. The solution is represented in the form of series in spherical wave functions with coefficients dependent on the contour of the refractive index. These coefficients are found by means of the elaborated piecewise continuous hyperbolic approximation. The obtained results considerably extend the set of the scattering problems which can be solved in the explicit form. The new method reproduces the scattering experimental data more exactly than the Mie theory does [3]. The above reasoning can be used when solving the problem of scattering by solids of revolution in case of the normal incidence.

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Calculation of Optical Fields Inside the Spheroidal Particles of Cosmic Dust: Comparison of Different Methods (GMT, T-matrix, SVM)

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The thermal effects (heating, evaporation, destruction and so on) arising at the electromagnetic wave interaction with particles of cosmic dust play an important role in physics of ISM. The computer modeling of such effects divides into two major steps: a) the calculation of optical fields inside the particle grounded on the theory of light scattering by small particles; b) the solution of heat-conduction equation over the time-spatial grid with sources calculated in the first step. In so doing the choice of the particle model is of basic importance. The model of homogeneous spheroid is a relatively good approximation to the real shape of grain. It is known that the T-matrix method, widely used for light scattering calculation for spheroidal grains, may be reasonably implemented for internal field provided that the Rayleigh hypothesis for internal problems is valid [1], that hinders the correct computing of fields for spheroids with $a/b > \sqrt{5}$ (a, b–the major and minor semiaxes).

In this connection it is appropriate to use other exact methods, specifically the General Multipole Technique (GMT) (named as the Discrete Sources Method also)[2] and Separation of Variables Method (SVM). The parallel employment of several significantly different methods provides a possibility to obtain the benchmark results. We developed computer codes for the optical field calculation inside prolate spheroidal particles using three mentioned approaches. Regrettably, we met with some difficulties in the elaboration of codes for oblate spheroid (especially for SVM). We suppose that such codes will be realized some later.

The GMT is based on the idea of alternative choice of complete function systems to approximate the wave fields. Such functions are built on the base of fundamental solution of Maxwell's equations and, as a rule, have quite simple form. It is essential that the function system used can be fitted in some extent to the geometry of a scatterer. In particular, the system of lowest order multipoles distributed along symmetry axis of the scatterer we used in our calculations is proved to be almost independent on stretchedness of the body. In contrast, analogous calculations in the frame of conventional T-matrix approach are failed as the body stretchedness exceeds some limit. Unlike SVM, the GMT is not bound to a specific geometry of a scatterer. Moreover, the possibility to distribute the fictious sources in complex space imparts additional flexibility to this method.

Our SVM-code for internal field is based on approach of Voshchinnikov and Farafonov for external problems [3] which is considerably more efficient that other SVM-schemes from the computational point of view. The characteristic features of this approach are the division of fields into two parts (axisymmetrical and nonaxisymmetrical) and new way to select the expansion basis for the second part.

We compared the elaborated codes with respect to computer time, precision and effectiveness for internal field calculation for prolate spheroidal dust grains of astronomical silicates.

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Thermal Effect of Radiation on Dust Particles

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Cosmic dust grains are an important component of the interstellar medium. They play a central role in the star-formation process, the energy balance of gas clouds and so on. For the calculation of the thermal effect of various kinds of radiation on dust particles the absorption and heating of particles have to be known over a wide interval of particle composition and sizes. As dust grains may be composite collections of particles of distinct materials, including voids agglomerated together, such particles can be replaced by a series of concentric spherical layers, each of which has the optical properties of one material or vacuum [1]. At first we will consider only composite grains with two materials: amorphous carbon and vacuum. For the calculations we use optical constants of actual amorphous carbon (the "Be 1" tabulated in [2]). At incident wavelength $\lambda = 0.55$ μm the refraction index of carbon is $n = 2.08$, the absorption index of carbon is $k = 0.801$. These particles were simulated by assuming the two-layered spheres. The core of the particles are filled with the air. The shell contains amorphous carbon.

We developed some computer programs for calculations of internal intensity distributions in two-layered particles and heating of them. the mathematical formulation of the problem of heating of two-layered particles consists in the solution of the heat-conduction equation in spherical coordinates with corresponding initial and boundary conditions taking into account the nonuniform heat release inside the particles and temperature dependences of optical and thermophysical properties of particle material.

The internal intensity distribution inside two-layered air-carbon particles has a substantially inhomogeneous character. During the heating process the location of maximum heat evolution plays an essential role. Inside the considered air-carbon particles the region of maximum internal absorbed energy is localized near the particle surface in the illuminated hemisphere. The absorbed energy density in the illuminated part of the particle shell is almost 5-6 times higher than in the shadow part. In Fig.1 the inner particle radius is $R_2 = 0.5$ μm.

Computer simulation of the two-layered hollow particles heating shows that the dependences of the heating time of the air-carbon particles on their sizes are very interesting. Heating time of the two-layered particles substantially depends on the particle radii. The growth of the particle radii leads to the increase of the heating time for all thicknesses of carbon shell. The thinner is the air-carbon particle shell, the more rapid is the heating of the particle for the same particle inner radii. The greatest heating time takes place for the homogeneous carbon particle. It is four times greater than the heating times of the hollow air-carbon particles. If we compare the absorption efficiences of such particles, we see that with increasing the thickness of the particle shell the absorption of the particles increases too. Homogeneous carbon particles have the greatest absorption. It would seem that the homogeneous particles must heat the most rapid. But the dependences of the heating time of two-layered particles on the particle radii have diametrically opposed character. This fact is explained by the influence of the internal energy distributions in the two-layered particles, even though the temperature distributions inside these particles during heating are closely uniform. This shows the use of taking into account the heat release distributions inside the two-layered particles in solving problem of heating of multilayered particles by radiation.

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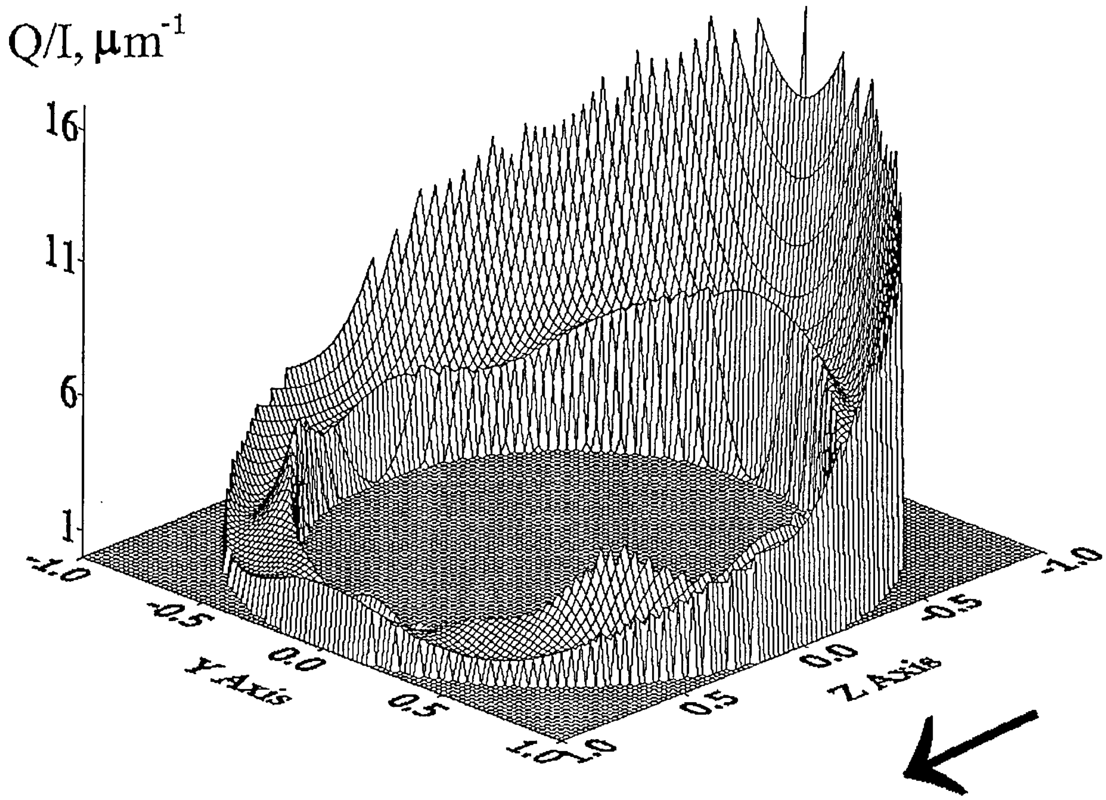

Figure 1: Distribution of absorbed energy inside air-carbon two-layered particle. The ratio of the core radius and inner particle radius is 0.8.

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New Light Scattering Tools to Develop Cosmic Dust Models

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A series of exact and approximate methods, algorithms and computer codes to calculate the light scattering by particles of different shapes and structures were developed by the authors during the work within a joint INTAS grant. The new methods of light scattering theory, including new mixing rules of the Effective Medium Theory, were compared with older ones and the range of their applicability was outlined. Some of the exact approaches, in particular the T-matrix and Separation of variables methods, were analytically and numerically investigated to reveal their limitations in the very general case. The work on the light scattering theory is planned to be supplemented by experimental measurements for cosmic dust analogues. First calibrating experiments are in progress.

The project will include the creation of an electronic Database of Optical Properties (DOP) of small particles available via the Internet. The DOP will contain original codes, benchmark results (well checked values of cross-sections, matrix elements and so on), a graphic library of the optical properties of various scatterers, references to papers on the subject, links to related Internet resources, etc. The tools under construction will be (a few already are) available at the site *http://www.astro.spbu.ru/staff/ilin2/INTAS.* They can be useful for development of new models of inhomogeneous non-spherical cosmic dust grains.

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Exact Computations of Coherent Backscattering

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Coherent backscattering, otherwise known as weak photon localization, is a remarkable phenomenon caused by constructive interference of waves propagating along reciprocal multiple-scattering paths in a discrete random medium. A well-known manifestation of coherent backscattering is an intensity peak centered at exactly the backscattering direction. The amplitude of the peak depends on the polarization states of the incident and reflected beams and can be as large as a factor of 2. When the incident beam is unpolarized, then the backscattering intensity peak is accompanied by a sharp asymmetric peak of negative polarization with a minimum centered at a very small phase angle. This phenomenon has been called the polarization opposition effect and has the same physical origin as the spatial anisotropy of the backscattering intensity peak in the case of a linearly polarized incident beam. It has been suggested that coherent backscattering could be a contributor to some effects observed for solar system bodies in visible light and at radiowave frequencies. However, accurate theoretical computations of weak localization are difficult and have been used in analyses of observational data in only a handful of publications. In this paper we briefly review the existing exact computations of coherent backscattering.

The physical origin of weak photon localization is illustrated by Fig. 1. The waves scattered along the two conjugate paths interfere, the interference being constructive or destructive depending on the phase difference $k(\mathbf{r}_N - \mathbf{r}_1)(\hat{n}_{ill} + \hat{n}_{obs})$, where k k is the wave number. If the observation direction is far from the exact backscattering direction given by $-\hat{n}_{ill}$, then the two waves interfere in different ways, and the average effect of interference is zero due to the randomness of particle positions. Consequently, the observer measures some average, incoherent intensity well described by the classical radiative transfer theory. However, at exactly the opposition ($\hat{n}_{obs} = -\hat{n}_{ill}$), the phase difference between conjugate paths involving any group of particles is identically equal to zero and the interference is always constructive, thereby resulting in a coherent backscattering intensity peak.

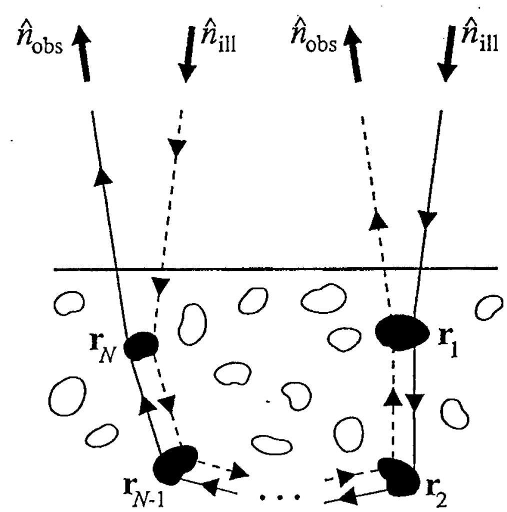

Fig. 1

An exact computation of the coherent backscattering effect based on solving the Maxwell equations is feasible only for few-component clusters and is complicated by several factors. First, the scattering pattern for a monodisperse cluster in a fixed orientation is always heavily burdened by multiple maxima and minima resulting from the interference of partial waves scattered by the cluster components and by the intricate resonance structure of the single-scattering contribution. Second, the scattering pattern can be further affected by near-field effects that result from component particles being in a close proximity to each other. Third, simple trigonometry shows that the angular width of the coherent backscattering intensity peak is of the order of $1/k\langle d\rangle = \lambda/2\pi\langle d\rangle$, where $\langle d\rangle$ is the average distance between the cluster components and λ is the wavelength in the

surrounding medium. Therefore, the peak may be too broad to be reliably identified unless the cluster components are separated widely enough. However, increasing the distance between the cluster components diminishes the contribution of multiple scattering and, thus, the amplitude of the coherent backscattering peak, thereby making it difficult to detect. To smooth the effect of the first factor out and make the backscattering peak detectable, one must compute a scattering pattern that is averaged over particle sizes, cluster orientations, and distances between the components. Furthermore, the average distance between the cluster components must be much larger than the size of the components and the wavelength, but yet small enough so that the multiple-scattering contribution to the total signal be still significant.

Mishchenko [4] used the exact superposition T-matrix method to compute far-field scattering by polydisperse, randomly oriented clusters composed of two equal wavelength-sized spheres with varying center-to-center distances. He computed the ratio of the intensity scattered by the clusters to that scattered by two independent polydisperse spheres of the same average size assuming unpolarized incident light. Figure 2 shows this ratio versus scattering angle (angle between the incidence and scattering directions) calculated for $k\langle d\rangle = 25$, ,average component sphere size parameter $k\langle a\rangle = 5$, and relative refractive index $m = 1.2$. The curve clearly exhibits a backscattering enhancement with an angular width comparable to $1/k\langle d\rangle$ and an amplitude of about 1.03. Mishchenko found that this feature persisted with varying $k\langle d\rangle$, $k\langle a\rangle$, and m, thereby indicating that it was indeed caused by coherent backscattering.

The amplitude of the coherent backscattering peak (the ratio of the intensity in the center of the peak to the background value) can be significantly greater for very large collections of particles because of a much stronger contribution of multiple scattering. The exact theory for large particle collections is very complicated and has been developed only for the case of reflection of light by a semi-infinite layer composed of nonabsorbing Rayleigh scatterers [1]. An important exact result was obtained by Mishchenko [2], who used Saxons reciprocity relation to show that the photometric and polarization characteristics of coherent backscattering at exactly the backscattering direction as well as outside the backscattering peak can be expressed in terms of the solution of the classical radiative transfer equation.

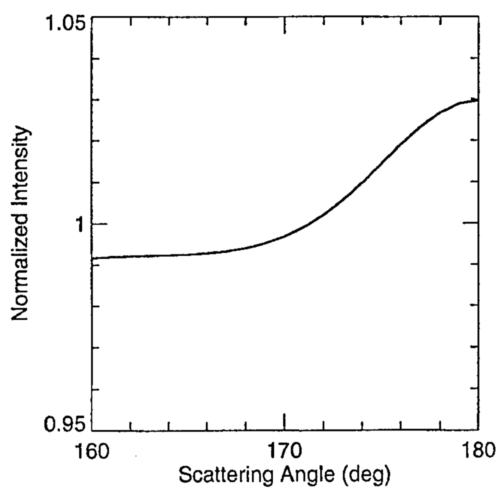

Fig. 2

Mishchenko et al. [5] used the exact theory for Rayleigh scatterers to compute the characteristics of coherent backscattering in the case of unpolarized light illuminating a semi-infinite slab. Figure 3 shows the enhancement intensity factor and the degree of linear polarization as functions of a dimensionless angular parameter q. The amplitude of the backscattering intensity peak is ≈ 1.5368 and its half-width at half-maximum is ≈ 0.597. The reflected polarization, being zero at opposition, becomes negative with increasing q, rapidly grows in absolute value, and reaches its minimal value $P_{min} \approx 2.765\%$ at a reflection direction very close to opposition ($q_P \approx 1.68$). The peak of negative polarization is highly asymmetric so that the half-minimal polarization value 1.383% is first reached at $q_{P,1} \approx 0.498$, which is even smaller than the value $q_\zeta \approx 0.597$ corresponding to the half-width at half-maximum of the backscattering intensity peak, and then at a much larger $q_{P,2} \approx 7.10$. This unusual behavior of polarization at near-backscattering angles was called by Mishchenko [3] the polarization opposition effect.

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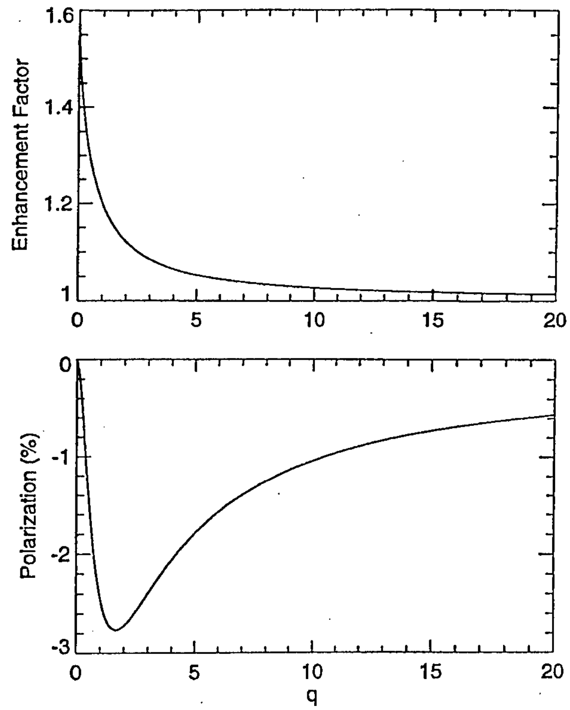

Fig. 3

Comparative Study of Coherent Backscattering and Shadowing Mechanisms Contribution in the Formation of Brightness and Polarization Opposition Effects for Different Atmosphereless Solar-System Bodies

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The scattered radiation is a primary source of observational information about the cosmic dust. Observations at small solar phase angles (the region of the well known opposition effects) are particularly important for understanding properties of the scattering surface as well as of the radiation scattering process itself. The brightness and polarization opposition effects are very sensitive to the size of regolith grains, their packing, and composition. Therefore, by studying the amplitude of scattered radiation as well as its angular and polarization characteristics at small phase angles one can obtain information about the properties of the optically interacting layer of the regolith, for instance about the structure and the bulk composition.

According to the coherent backscattering theory the photometric opposition effect (the intensity spike) and polarization opposition effect should accompany one another. There are many photometric observations of different atmosphereless solar-system bodies (ASSBs) obtained for both wide and narrow ranges of phase angles. However, measurements of polarization at very small phase angles are very rare. Therefore, the purpose of this work is twofold: (1) to obtain precise measurements of polarization for several high-albedo objects at the smallest possible phase angles, for which the photometric opposition effect can still be observed, and (2) to analyze existing photometric and polarimetric observations of ASSBs surfaces in order to estimate the contribution of coherent backscattering and shadowing mechanisms to the brightness and polarization opposition effects.

We present new UBVRI polarimetric observations of the Galilean satellites of Jupiter, Saturn's satellite Iapetus as well as the asteroid 64 Angelina near the opposition. They show that there is a sharp peak of negative polarization centered at a very small phase angle which is superimposed on the negative branch of the regular phase angle polarization curve. Our observations, as a whole, confirm the theory of coherent backscattering: the angular half-width and the position of polarization peak are very near to those predicted by the backscattering theory and are comparable to that observed for intensity spike. At the same time, the parameters of the observed polarization peak and the brightness spike are different for different bodies, e.g., for Europa and for 64 Angelina. Therefore, it is plausible to assume that even within the framework of the same mechanism, the difference in particle properties (albedo, size, refractive index, porosity) can result in different photometric and polarimetric opposition effects.

A detailed study of available magnitude-phase and polarization-phase curves for high, moderate and low albedo ASSBs (including asteroids, satellites of planets, rings of Saturn, and some details of the Lunar and Martian surface) is performed. The behavior of color indexes of several ASSBs near opposition is also investigated. The amplitude and the half-width at half-maximum of intensity and polarization peaks, as well as their wavelength dependence have been obtained.

The results of this study will be summarized briefly and possible explanations for the correlations obtained will be discussed in terms of the relative contribution of two main mechanisms, causing the oppositions effects: namely, shadowing and interference.

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Simulation of the Coherent Opposition Effects for Discrete Random Media

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Coherent backscattering of light by disordered medium results in well-known backscattering enhancement phenomenon, which manifests itself as a narrow intensity peak, centered at the exact backscattering direction. In the case of unpolarized incident wave this effect can be accompanied by the polarization opposition effect that may show a narrow peak of negative polarization at small phase angle α. Theoretical description of coherent backscattering of light by disordered medium is too complicated even in the case of rarefied media. Theory of coherent backscattering by semi-infinite medium composed of nonabsorbing point-like scatterers has been considered in Ref.1. However the dependence of the opposition effects on the properties of the scatterers (size parameter, refractive index, ets.) is insufficiently studied. The rigorous equations for coherent and incoherent components of reflection matrix for a layer of disordered medium composed of chaotically oriented arbitrary scatterers have been obtained in Ref.2. In the basis of circular polarization the scattering matrix has been presented as a sum of two matrices $S_{pn\mu\nu} = S^{(nc)}_{pn\mu\nu} + S^{(co)}_{pn\mu\nu}$, where matrix $S^{(nc)}_{pn\mu\nu}$ corresponds to incoherent part of scattered light, matrix $S^{(co)}_{pn\mu\nu}$ corresponds to coherent one, $p, n, \mu, \nu = \pm 1$. The equations describing these matrices are too complicated for numerical calculations. To consider the influence of particle properties on the opposition effects, we use these equations in the double-scattering approximation for semi-infinite medium. In this approach the expressions are considerably simplified. Matrix $S^{(nc)}_{pn\mu\nu}$ can be written as:

$$S^{(nc)}_{pn\mu\nu} = -\frac{n_0 \cos\vartheta}{2kIm(\varepsilon)(1-\cos\vartheta)} \sum_L d^L_{M_0N_0}(\vartheta) A_L^{(pn)(\mu\nu)}, \tag{1}$$

$$\begin{aligned} A_L^{(pn)(\mu\nu)} &= \chi_L^{(pn)(\mu\nu)} + \frac{\pi n_0}{k^3 Im(\varepsilon)} \sum_{qq_1} \chi_L^{(pq)(\mu q_1)} \sum_l \chi_l^{(qn)(q_1\nu)} \Bigg(\int_0^{\pi/2} d^L_{M_0N}(\omega) d^l_{M_0N}(\omega) \frac{\cos\vartheta \sin\omega d\omega}{\cos\vartheta - \cos\omega} \\ &+ \int_0^{\pi/2} d^L_{M_0N}(\pi-\omega) d^l_{M_0N}(\pi-\omega) \frac{\sin\omega d\omega}{1+\cos\omega} \Bigg). \end{aligned} \tag{2}$$

Here matrix $S^{(nc)}_{pn\mu\nu}$ is normalized to a unit of surface area, n_0 is the concentration of particles in the medium, $k = 2\pi/\lambda$, λ is the wavelength of the incident radiation, symbol d denotes the Wigner function, ϑ is the scattering angle ($\vartheta = \pi - \alpha$), $M_0 = \nu - n$, $N_0 = \mu - p$, $N = q_1 - q$ ($q, q_1 = \pm 1$), ε is the complex effective refractive index of the medium. Coefficients $\chi_L^{(pn)(\mu\nu)}$ are the expansion coefficients in series of the Wigner d function of the scattering matrix elements for isolated particle.

Coherent part of scattered radiation is described by

$$S^{(co)}_{pn\nu\mu} = -\frac{\pi n_0^2 \cos\vartheta}{k^4 Im(\varepsilon)(1-\cos\vartheta)} \sum_{LMlmqq_1} \zeta_{LM}^{(pq)(\mu q_1)} (-1)^l \zeta_{lm}^{*(\nu q_1)(nq)} i^{-|m-M|} B^{(pn))(\mu\nu)}_{LMlm}, \tag{3}$$

$$\begin{aligned} B^{(pn)(\mu\nu)}_{LMlm} &= \int_0^{\pi/2} d^L_{MN}(\omega) d^l_{mN}(\omega) \frac{c^{|m-M|} \sin\omega d\omega}{\sqrt{c^2+f^2}(f+\sqrt{c^2+f^2})^{|m-M|}} \\ &+ \int_0^{\pi/2} d^L_{MN}(\pi-\omega) d^l_{mN}(\pi-\omega) \frac{c^{|m-M|} \sin\omega d\omega}{\sqrt{c^2+f^{*2}}(f^*+\sqrt{c^2+f^{*2}})^{|m-M|}}, \end{aligned}$$

$$
\begin{aligned}
f &= 2Im(\varepsilon) + \cos\omega\Big(Im(\varepsilon)(1 - \frac{1}{\cos\vartheta}) + i[Re(\varepsilon) - 1](1 + \frac{1}{\cos\vartheta}) + i(1 + \cos\vartheta)\Big), \\
c &= \sin\vartheta \sin\omega. \qquad (4)
\end{aligned}
$$

Using the above presented formulae we calculated the angular dependence of the linear polarization degree $P = \sum S_{pn-pn}/\sum S_{pnpn}$ and the normalized intensity $I = \sum S_{pnpn}(\vartheta)/\sum S_{pnpn}(\pi)$ for semi-infinite medium of spherical particles at different values of the filling factors ξ, size parameter $x = k\tilde{a}$, ($\tilde{a}$ is radius of particle) and refractive index $\tilde{m}$. The following value of the effective refractive index of the medium was used $\varepsilon = 1 + in_0 C_{ext}/2k$, where C_{ext} is the mean optical extinction cross section. Some examples of calculations are presented on Fig.1 and Fig.2.

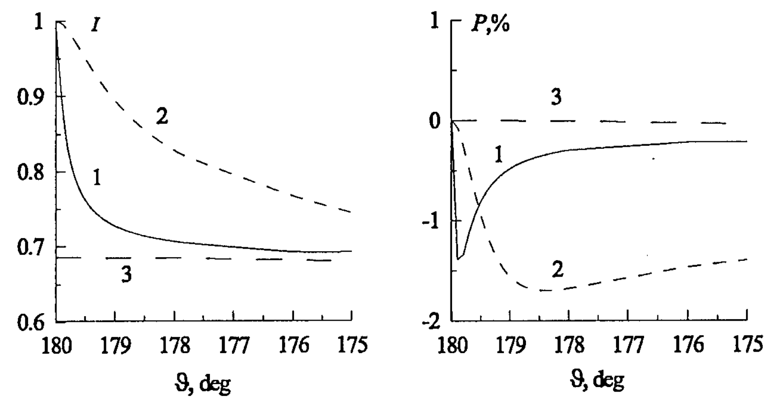

Figure 1: Intensity I and linear polarization degree P vs scattering angle ϑ for $x = 3$, $\tilde{m} = 1.35+0i$, $\xi = 0.001$ (line 1), $\xi = 0.01$ (line 2). Line 3 corresponds to incoherent part of scattered light.

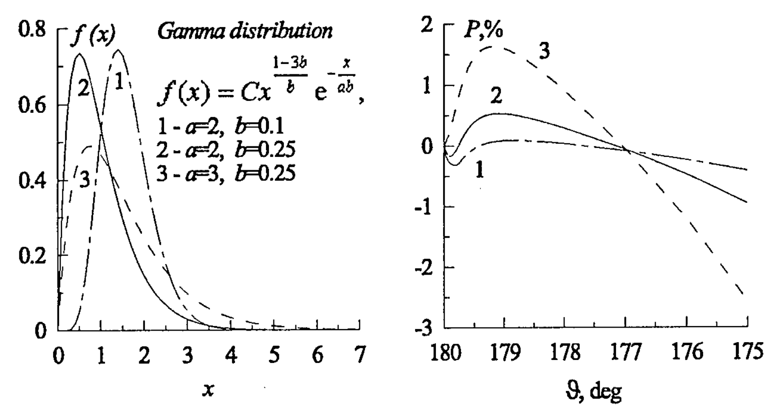

Figure 2: Linear polarization degree P vs scattering angle ϑ for different gamma distributions of particles. $\tilde{m} = 1.5 + 0i$, $\xi = 0.002$.

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Laboratory Modeling of Photometric and Polarimetric Opposition Effects for Cosmic Dust and Planetary Regoliths

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To better understand photometric and polarimetric features of cosmic dust and planetary regoliths using available and future observational data, laboratory simulated measurements are needed. They are also necessary to verify theoretical light-scattering models. We present here results of our photometric and polarimetric measurements of samples with different structure and albedo [1]. The studies were carried out by the small-phase-angle laboratory polarimeter of Kharkov observatory at the wavelength 0.63 microns and phase angles 0.2-12 degrees. We have obtained the following results.

A strong particle-size dependence of negative polarization parameters for powdered dielectric surfaces was found, whereas the opposition effect characteristics are comparatively more inert on size particle changing. We studied particle-size separates of alumina (0.1, 0.5, 1, 4, 7, and 12 microns). At the sizes more than 1 microns the depth of negative polarization branches does not exceed 0.2%. It is maximal (near 0.8%) for the 0.1 microns fraction. This result can be considered as an important test for available and future theoretical models of light scattering.

Surfaces with submicron scale structure, like MgO, show a dramatic dependence of negative polarization on volume density. The sharply asymmetric negative polarization branch of MgO coatings with the minimum centered near 1 deg. becomes after sample compressing almost symmetrical with the minimum position near 10 deg. This points out that the regular (wide) negative polarization branch and so-called polarimetric opposition effect (a narrow negative polarization surge at extremely small phase angles) have perhaps a common origin, related with the coherent backscatter mechanism.

Surfaces formed by smoked coatings of MgO and carbon soot, despite the extremely different albedo and opposition spikes, show prominent and rather similar negative polarization branches with minimum near 1.5 degrees and depth near 0.8%. Microphotographs obtained with a scanning electronic microscope show that the surfaces consist of particles with size mainly less than the wavelength.

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Negative Polarization of Light Scattered by Cometary Dust and Planetary Regoliths

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Simulations of polarization characteristics of cometary comas and planetary regoliths are important to understand physical properties of cosmic dust. At small phase angles the dust cometary comas [1] and planetary regoliths [2] reveal the negative polarization branch. Among different physical mechanisms that can contribute to the negative polarization effect, the coherent backscattering enhancement is considered to be most important [2]. Assuming that the cometary dust and planetary regolith particles are aggregates of smaller particles, we study the effectiveness of this mechanism using a ray-tracing approach developed in [3], [4]. In our work we show that the negative polarization of the aggregate particles can be formed by the effect of coherent backscattering enhancement. In our modeling we used aggregates (clusters) that have near spherical shapes consisting of 1000 small particles. The aggregates have an in-average-constant volume density equal to 0.3. The composing particles are considered to be spherical as well as random shaped. In both cases we used DDA method to calculate scattering indicatrix [5]. The equivalent size parameter of the particles is of about 2 and the refractive index equals to 1.5+0.4i (the single-particle albedo is 0.41). To simulate scattering properties of the clusters, we used the indicatrices averaged over particle orientations.

Our simulation shows, in particular, that there are strong dependences of negative polarization branches on (1) the shape of composing particles and (2) the number of scattering orders kept in the modeling. In our case the cluster consisting of particles with random shapes shows more prominent negative polarization branch than in case of spherical monomers. Orders higher than sixth one contribute to the total scattering flux very small.

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Some Properties of Polarization Opposition Effect. An Application to Saturn's Rings Observations

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Radiation scattered by medium can be presented as sum of incoherent and coherent parts. Incoherent part depends on medium properties relatively weakly and is described by the radiative transfer theory. Coherent part is produced by constructive interference of multiple scattered light and manifests itself in backward direction as well known photometric and polarimetric (polarization) opposition effects. The coherent part is more sensitive to properties of scattering medium than incoherent one. However the theoretical description of the interference effects is extremely intricate problem. The complete solution of the problem has been recently developed for semi-infinite medium composed of nonabsorbing point-like scatterers (see [1] and Refs. there). One of characteristics that can be used to determine medium properties is the position of minimum of linear polarization degree α_m. For semi-infinite medium and nonabsorbing point-like scatterers numerical calculation gives [1]:

$$\alpha_m = \frac{1.68}{kL}. \tag{1}$$

Here L is the photon transport mean free path, k is the wave number.

In work [2] the rigorous expressions of diffuse and coherent parts of scattered radiation were obtained for a layer of discrete random medium composed of chaotically oriented arbitrary scatterers. But expressions for the coherent part are too complicated for numerical calculations. Therefore the double scattering approximation and model of semi-infinite medium was used to obtain some numerical results [3]. The characteristics of polarization opposition effect was shown to be strongly dependent on the concentration and properties of scatterers in the medium. In particular, the linear polarization degree at small phase angle may be negative as well as positive one and it is possible to obtain bimodal angle dependence of the linear polarization degree.

Now we consider another extreme scattering model that corresponds to light scattering by optical thin medium. For such a kind of medium composed of not very large scatterers the expression for α_m can be found in analytical form:

$$\alpha_m = \frac{\sqrt{\sqrt{2}(\sqrt{2}+2)}}{kL} \simeq \frac{2}{kL}. \tag{2}$$

Numerical calculations in double scattering approximation for semi-infinite medium composed of non point-like scatterers show similar to (1) and (2) dependence of position of negative polarization minimum: $\alpha_m = \frac{K}{kL}$. But coefficient of proportionality K is defined by scatterers properties.

The expression (2) for optical thin medium is in a good accordance with that for semi-infinite medium and nonabsorbing point-like scatterers (see Eq.(1)). In both cases the position of linear polarization degree extremum is defined by the photon transport mean free path only. The photon transport mean free path depends on concentration and particle properties. In the case of nonabsorbing particle it can be determined as:

$$L = \frac{1}{nC_{sca}(1- < cos\vartheta >)}, \tag{3}$$

where C_{sca} is scattering cross section, n is the concentration of scatterers in the medium and $< cos\vartheta >$ is the asymmetry parameter. For media of point-like scatterers the photon transport mean free path is identical to the photon mean free path.

As an example of using above presented relation we estimated surface properties of the Saturn's rings particles. The most rings particles are suggested to be centimeter to several meters in size. Their surfaces are like snow or frost [4]. Telescopic polarimetric observations of the Saturn's rings show the negative linear polarization degree at small phase angles. Such polarization behavior was explained by interference of multiple scattered waves by clathrate of rings particles [5]. Resent analysis of numerous earth-based observations shows bimodal angle dependence for linear polarization degree of the Saturn's rings and the Galilean satellites of Jupiter [6]. The value of α_m for first (sharp) polarization peak is about 0.5^0 whereas for second (smooth) one is about $3^0 - 4^0$. One of possible explanations of such bimodal behavior of linear polarization degree is following. The smooth polarization peak is formed as well as for cometary dust by closely packed aggregates whose size is order of wavelength of incident radiation whereas the sharp polarization peak is a result of constructive interference of waves scattered by different aggregates.

Within above mentioned explanation of polarization behavior there is a possibility to estimate filling factor of aggregates for surface of rings particles $\xi = 4\pi a^3 n/3 = 4\pi x^3 n/3k^3$ (a is the effective radius of aggregate, x is the effective size parameter). From Eqs. (2), (3) we have

$$\xi = \frac{2\pi x^3 \alpha_m}{3k^2 C_{sca}(1- < cos\vartheta >)}. \tag{4}$$

The numerical calculations of Eqs. (4) for refractive indexes $1.2 \div 1.33$ and $5 \leq x \leq 20$ give for filling factor $\xi \simeq 0.02 \div 0.3$. The smooth negative peak can be produced by aggregates consisting of not very large number of particles with size parameter $x_0 \sim 1$. Thus assuming that effective size parameter of cluster grain is order of $x_0 \sim 1$ (see, Ref.4) and number of cluster grains is order of 10^2 or 10^3 ($x \simeq 10$), estimation of filling factor of aggregates for surface of rings particles gives $\xi \approx 10^{-1}$.

It is necessary to remark that above presented expressions and fulfilled estimation of the filling factor is valid if size of aggregates is less or order of wavelength and concentration of aggregates is small enough to neglect shadow effect.

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Experimental Determination of Scattering Matrices as Functions of the Scattering Angle

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We will report on a light scattering instrument to measure scattering matrices as functions of scattering angle of small irregular particles. With this instrument we can measure the scattering matrices of various aerosols and cosmic dust analogs. Measured scattering matrices of cometary analogs [1] will be discussed by Muñoz et al. [2] (this conference).

In our experimental setup a He-Ne laser or a He-Cd laser is used as a light source (wavelengths 632.8 nm and 441.6 nm). This light is scattered by randomly oriented particles located in a jet stream. We employ polarization modulation in combination with lock-in detection to obtain the angular profiles of the elements of the four by four scattering matrix, that describes the scattering process. This matrix contains 16 elements, eight of which are identically zero. The other elements depend on the size, shape and optical properties of the particles. We will present results of measurements on water droplets that are used as a test to ensure that the setup works properly.

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Scattering Matrices of Cometary Analogues

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Olivine particles occur in many astronomical objects, such as comets, asteroids, circumstellar envelopes and planetary nebulae. In many cases the light scattering properties of these particles are required for the interpretation of observations of these objects. Experimental measurements of a Mg-rich olivine sample [1], performed with the experimental setup presented by Volten et al. [3], (this conference), will be compared with polarization data of different comets. In addition, we will show that the use of Lorenz-Mie theory for nonspherical olivine particles can result in substantial errors. Since there is not an exact solution for the scattering of light by nonspherical dust particles covering all sizes and shapes that occur in nature, we propose as an alternative the use of our measured results for modeling purposes. As an example, we will present some results of a Monte Carlo code to compute energy fluxes in cometary nuclei [2] (this conference).

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Monte Carlo Modeling of Dusty Cometary Atmospheres Including Polarization

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We present some results derived from Monte Carlo modeling of spherical-shell cometary atmospheres. Our model, wich includes the effects of polarization, constitutes an improved version of that by Salo [1]. The code has been designed to compute both the input radiation on the nucleus surface and the output radiation. This will have specific applications regarding the interpretation of near-nucleus photometry, polarimetry, and imaging such as planned for the near future space probes. We address here the effect of including the full 4×4 scattering matrix into the calculations of the radiative flux impinging on cometary nuclei. As input of the code we used realistic single scattering phase matrices derived by fitting the observed behavior of the linear polarization versus phase angle in cometary atmospheres. The observed single scattering linear polarization phase curves of comets are found to be fairly well represented by a mixture of Mg-rich olivine particles and small carbonaceous particles. The input matrix of the code is thus given by the phase matrix for olivine as obtained in the laboratory [2], (this conference), plus a variable scattering fraction phase matrix for absorbing carbonaceous particles. Particularly, these fractions are found to be 3.5% for comet Halley and 6% for comet Hale-Bopp, for which the greatest percentage of all the observed comets was found. The total input fluxes computed by ignoring the polarization effects are found to show differences as large as 10% with respect to the fluxes obtained when the full scattering matrix is considered into the calculations.

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Polarimetric Properties of the Dust in Disintegrating Comets

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Usually properties of cometary dust particles are deduced from observations of grains already ejected from the nuclear surface. Disintergation of comets, which is rather frequent phenomenon in comets, provide a good opportunity to study the internal composition of their nuclei. In the last few years we have carried out the polarimetric and photometric observations of several comets which have been disintegrated to different degree. They are: C/1996 B2 (Hyakutake), D/1996 Q1 (Tabur), D/1999 S4 (LINEAR), and C/2001 A2-B (LINEAR). We present results of observations and compare properties of dust particles of these comets using the CCD imaging, which were obtained with the focal reducer of the 2-m telescope at the Pik Terskol Observatory and aperture polarimetry and photometry obtained with the photometer-polarimeter of the 0.7-m telescope at the Astronomical Observatory of Kharkiv National University.

Comet C/1996 B2 (Hyakutake). Several fragments (condensations) which were ejected from the nucleus and moved along the tail, were observed (see e.g [1]). Our observations have not revealed any peculiarities in polarization and color of comet Hyakutake in comparison with other dust-rich comets.

Comet D/1996 Q1 (Tabur). The polarimetric, photometric and spectral observations of comet Tabur were carried out on October 5-10 1996, shortly before catastrophic decrease of its brightness in late October 1996. Since neither outbursts nor a disruption of the nucleus were observed, one can assume that a sharp decreasing of comet brightness can be caused by deactivation of the nucleus. According to similarity of orbital parameters, gas-rich comet Tabur and dust-rich comet C/1988 A1 (Liller) are the fragments of a common parent body. However, they are strongly distinguished with respect to gas-to-dust ratio [2]. Nevertheless, polarimetric properties of dust in comet Tabur for the near nucleus region is similar to that for dust-rich comets. At the same time the polarization degree of Tabur depends strongly on the area of the coma. The reasons for this will be discussed.

Comet D/1999 S4 (LINEAR). The comet fragmented several times which was manifested by a series of sporadic outbursts in June and July before the final disintegration of nucleus after 23 July, 2000. Before the disruption, the phase dependence of polarization for this comet had a strong resemblance to that commonly observed for dusty comets. However, most of time, the spectral dependence of polarization was very unusual. The degree of polarization in the red filters was lower than in the green and the blue ones. Similar effect was recently detected in comet 21P/Giacobini-Zinner [3]. Both comets belong to the taxonomic class of carbon chain-depleted comets [4]. Most of the time, the comet had strong continuum spectrum with unusually high color index of dust, greater than 20% per 1000 Å. The dramatic change of polarization of comet C/1999 S4 (LINEAR) was observed during its final disruption after July 23. The degree of continuum polarization increased up to 31.1% on July 28.8 and up to 29.5% on July 29.8. The mean cometary color increased also. The red and blue regions of the coma were found on the color maps [5]. We interpret the observed photometric, polarimetric and colorimetric variability of the comet as a release of dust particles smaller than average and the subsequent separation caused by the solar radiation pressure.

Comet C/2001 A2 (LINEAR). During its approach to the Sun the comet displayed a series of sporadic outbursts due to partial fragmentation of nucleus. We observed the most brightness fragment of the comet - nucleus B. This fragment was gas-rich one, according to its low value of dust production rate (Af$\rho \leq$0.5m).

Dust in the comet was blue relatively to the Sun in the wavelength range 3450-5260 Å, and red in the wavelength range 5260-7128 Å. The blue color of dust is more often observed for the gas-rich comets [6]. In the near nuclear region, the polarization was similar to that of the dust-rich comets. Again, the polarization degree observed for a larger coma area was smaller, similarly as for comet Tabur. We conclude that the total disintegration of a comet, as it was in the case of comet C/1999 S4 (LINEAR), can result in significant changes of scattering properties of dust particles. Process of partial fragmentation of a comet not always causes changes of its polarization and color. Evolution of grain properties with the distance from the nucleus and the contribution of molecular emissions to continuum of gas-rich comets can result in more significant changes in their polarization and color.

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Ill-posed Problems of Light Scattering for Cometary Dust

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A considerable amount of interplanetary dust particles are produced by comets. The size distribution of the released or ejected particles is strongly dependent on the comet-Sun distance. Particulate properties are also depend on comet-specific characteristics. The total amount of dust produced by individual comets may be quite large, as the activity of dust cloud is dominant in comparison with the emissions in most active molecular bands (CN) (e.g. comet Kohoutek 1973f, or Hale-Bopp) [5].

The scattered light from comets is a superposition of radiation from both gas and dust. However, the gas contribution may be neglected in certain spectral bands in UV, VIS and near IR, as the dust emission is a selective process. Measurements of the scattered light in such spectral regions are a source of information on cometary dust. Dust tail analysis, e.g. a realistic time-dependent size distribution, is an ill-posed problems. The solution of these problems are affected by intrisic errors which may be quite large. Dollfus [1] has deduced the presence of large particles comparable to the wavelength when analysing polarized light in the continuum of the comet P/Halley. However, the large grains or flakes are probably intermixed by a mist of small particles. This is the reason of the most frequently used Mie theory to interpret polarization (scattered light intensity) curve [is this the reason, or is it simply because Mie theory is the quickest, and only practical method, to calculate the scattering from any large particles] [2], [4]. However, the measurements at different scattering angles (phase angles of the comet) should not be simply intermixed and analysed as a continuous polarization/(phase function) curve, as such access brings together an inconsistent data.

The ill-posed inverse problem is analysed in this contribution and the simple analytical formulae are obtained for spectral/angular dependence of the scattering phase function. The Mie theory approximation was applied to simulate a coma irradiance when the comet is located at large distances from Sun. In such a case the mainly submicron particles can be observed in dusty coma [9], [4]. The measurements of the dusty coma of comet P/Halley have shown a drastic reduction of the large particles, and the mode position near 0.1 μm [6]. Most of the cometary dust analyses consider a simple power size distribution function $f(r) \sim r^{-n}$, where r is the particle radius and n varies from 3 to 4 [7], [8]. However, it was shown that the power parameter increases with dust size. Therefore we have analysed a simple modified gama function $f(r) \sim r^a e^{-br}$ to fit the cometary dust distribution. The scattering phase functions are derived for both size distributions in analytical form. Such formulae can accelerate significantly the analysis procedures for the size distribution. The influence of nonsphericity of cometary dust particles on the data processing and size distribution retrieval is estimated. Optical parameters of dust particles are chosen to be consistent with polarimetric measurements of comet P/Halley [3]

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Size Distributions of Particles Obtained by Inversion of Spectral Extinction and Scattering Measurements

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The particles in the atmosphere attenuate and scatter light. Both the attenuation and the scattering is influenced by the particle's size and optical constants of the material. The wavelength dependent angular scattering and the extinction is a possibility to obtain information on the size distribution of the particles. The relation between optical properties and size is given by integral equations which have difficulties to be solved, since no unique solution exists.

In order to investigate the possibilities to obtain size distributions by inversion we have made measurements of the horizontal and vertical spectral attenuation of the atmosphere and the sky radiation at several locations in Europe. Furthermore the size distribution was measured at ground level with a cascade impactor at one location.

As inversion procedures we have used the skryad package by Nakajima, using the solar and sky radiation as input data and the inversion by King and an analytical procedure for the spectral attenuation measurements.

The volume size distribution obtained usually are bi- or tri-modal with one mode in the size range around a radius of 0.2 micrometers (accumulation mode) and a second peak between 1 and 2 micrometers. In the arid environment of Spain also a third peak between 3 and 10 micrometers has been observed. The size of the smallest mode shows a variation with humidity.

The comparison of the measured size distribution with the distributions obtained by inversion gives a good agreement, which proves, that the methods applied give reliable data.

Size Distribution of Dust in Comets Halley and Hale-Bopp, Based on the Thermal Emission and Albedo

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Cometary dust was studied extensively *in situ* for the first time in case of Comet Halley, e.g. by experiments DIDSY (recording the frequency and intensity of dust impacts on the detector area of the spacecraft Giotto, [4]) and PIA/PUMA (analyzing the elemental composition of the dust grains, and estimating also the mass and density of the grains, [3]). Recently, broadband infrared photometry of Comet Hale-Bopp, carried out by the photometer ISOPHOT on board of ISO [1], allowed also to investigate the emissivity of the grains, their size distribution, positions in coma and their chemical/mineralogical composition of dust in this bright comet.

Due to the different efficiency factors for absorption, scattering and emission, which depend mainly on size of the dust grain, its composition and temperature, the small, submicron particles are usually overheated if compared with the large, submilimeter particles. Moreover, these small particles are unable to contribute significantly to the thermal flux at submilimeter wavelength range. As a result, attempts to fit the measured continuum thermal flux from a mixture of various grains by the black body spectrum, give only the color temperature that can differ from the real physical temperature of grains.

Comet Hale-Bopp was observed by ISO/ISOPHOT (Infrared Space Observatory) five times at heliocentric distances 2.8 - 4.6 AU, in the spectral range of 3.6 - 170μm. Strong silicate features at 10 and 20 μm and significant contribution of large particles strongly supported the model of coma in which large mineral particles are more frequent than composed icy grains. The expression of size distribution according to Hanner [2] was used with three free parameters; the numerical value of them will be discussied and compared with the Halley data.

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Comet P/Halley 1982i: encounter by Giotto's impact detectors" *Astron. and Astrophys.* **187**, 719-741 (1987).

Retrieval of the Size Distribution of Magnetic Spherules Using the Extinction Data

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The dust particles in the space are produced by different mechanisms, and therefore have the different physical, and chemical properties. The more plausible dust model should take into account a detailed physical and chemical evolution of grains during their passage through various environments: diffuse and/or molecular clouds, star-forming regions and so on. Duley [3] studied core-mantle particles with feromagnetic and superparamagnetic cores and reached the conclusion that the magnetic susceptibility of the particles must be enhanced depending on the strenght of the interstellar magnetic field. Such an enhancement could be achieved by the inclusion of the ferromagnetic material (e.g. metallic Fe, Fe_3O_4, or other oxides or sulfides of iron). However, the cosmic dust particles are usually assumed to be dielectric objects and this assumption can significantly affect the retrieval of the particle characteristics such as the size distribution.

Many of the inverse problems in astrophysics of dust particles can be formulated in terms of a Fredholm integral equation of the first kind [1]. The extraction of information on the particle size distribution from multispectral extinction measurements is in general an ill-posed problem, which is notoriously difficult to solve. The major complexity to the solution brings the asphericity of the particle. Nevertheless, in many cases the main interest is in evaluating of the mean size of the particles or their mass distribution, which can be related to the size distribution. Therefore it has a sense to approximate the really shaped particles by the spheres of an identical volume. The existence of the magnetic spherules of an extraterrestrial origin is well-known for a long time [2].

The changes of the extinction are directly related to the changes of the particle size distribution. Weingartner and Draine [7] have constructed the size distribution for carbonaceous and silicate grain populations in different regions of the Milky Way, and have found a mode of the particle size distribution in the submicron range.

It can be shown that the small abundances of the magnetic materials in the particles significantly modify the obtained size distribution. To study an effect of particle permeability changes on retrieval of the size distribution we have constructed a simple model of spherules with the gamma distribution. We have found that the small increasing of the magnetic permeability μ, from 1.0 to say 1.2 will result in decreasing of the retrieved mode of the particle size distribution by a factor $\sim$ 4. The final behaviour of course depends on the chosen particle effective refractive index m and on the profile of extinction curve. Systematic numerical computations enable us to construct a simple formula, which bring together the modal radius r_m of the particle size distribution, main mode extinction curve (wavelength λ_m) and particle properties m, μ as follows

$$r_m \approx \frac{10\lambda_m - 5\pi|\mu - 1|}{16\pi|m - 1|}.$$

An example of the inversion of extinction curve (for star HD 202904 [8]) is presented in Fig. 1, where small inclusion of magnetic material in the cosmic dust particles is analysed, i.e. the particle relative permeability μ is increased from 1.0 to 1.2 (relative permeability of surrounding medium is 1.0 - 0.0i). We have accepted that relative error of the extinction data is about 5%, and used modified Tikhonov regularisation [6] to solve the inverse problem. The obtained size distribution $s(r) = \pi r^2 f(r)$ is a function of $f(r)$ [$\mu m^{-1}\ m^{-2}$], which represents a dust column density along the trajectory between the observer and source of the measured radiation. One can see that the neglection of the information on particle permeability can result in overestimating of the particle size.

Such fact can be quite important when evaluate the dynamical evolution of cosmic dust under the effect of electromagnetic radiation and gravity [4]. The correct information on the particle size have also an direct impact on evaluation of total mass of the interstellar material which is trapped in the Solar System. Kocifaj and Klačka have shown that the capture is most effective for sub-micron sized dust particles [5]. However, it was found that the total amount of the dust influx, which can be trapped depends significantly on the particle shape.

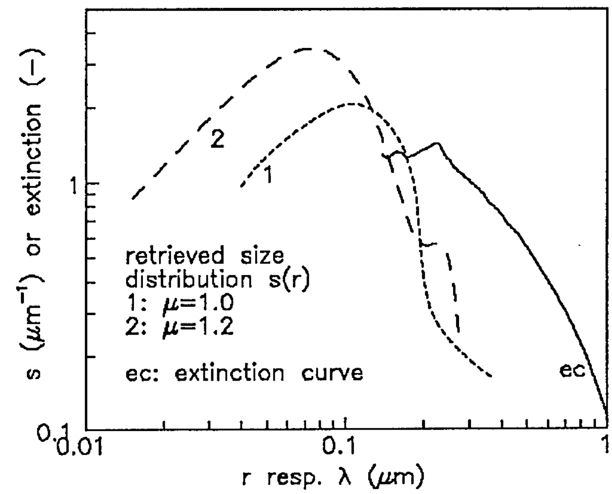

Figure 1: Retrieval of the extinction curve under two assumptions for the value of particle permeability μ: $|\mu| = 1.0$ (dielectric material), $|\mu| = 1.2$ (magnetic material).

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Modelling of Interstellar Extinction with Composite Dust Grains

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Modern investigations of chemical compositions for stars of several spectral types led to much lower reference abundance of the interstellar medium (the abundances of heavy elements in both the dust and the gas) [1]. Thereof all existing models of interstellar dust have appeared untenable. To explain the observed extinction law they require much greater element abundances in solid than are presented in the interstellar medium.

For overcoming this crisis we consider the new model of interstellar dust particles based on their composite nature. Grains are presented as multilayered spheres containing some amount of vacuum [2]. Also we estimate the influence of nonsphericity on the extinction efficiency. The model is applied for production of the interstellar extinction law toward the star ζ Oph.

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The Relation Between Extinction in the Ultraviolet and Diffuse Interstellar Bands

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Diffuse interstellar bands (DIBs), of which about 300 is currently known [1], continue to evade definite identification. The most probable candidates for the DIB's carriers are some carbon-bearing molecules or their ions [2]. As the relative strengths of the individual DIBs vary (sometimes considerably) from one line of sight to another, it is probable that many species of molecules are involved.

One of possible routes leading to identification is investigatiing how the DIBs relate to other phenomena of interstellar origin. Understanding the links between the molecules responsible for the DIBs and other components of the clouds can give us information about the physical properties, chemical composition and origin of the carrier molecules.

This work is concerned with the relation between several DIBs and ultraviolet continuum extinction, in the range covered by spectra from the IUE Final Archive. For a sample of about 40 early-type stars, we computed correlation coefficients between the DIB's strength (as measured by the central depth or equivalent width normalized by the $E(B-V)$) and all normalized colour excessess $E(\lambda_1 - \lambda_2)/E(B-V)$ in the IUE data range, adopting 20 Å step for both UV wavelengths.

We found that, for any given DIB, the correlation varies with the UV wavelengths, and that different DIBs correlate best with different parts of the ultraviolet extinction curve. This indicates that the DIBs are most probably related to different populations of grains.

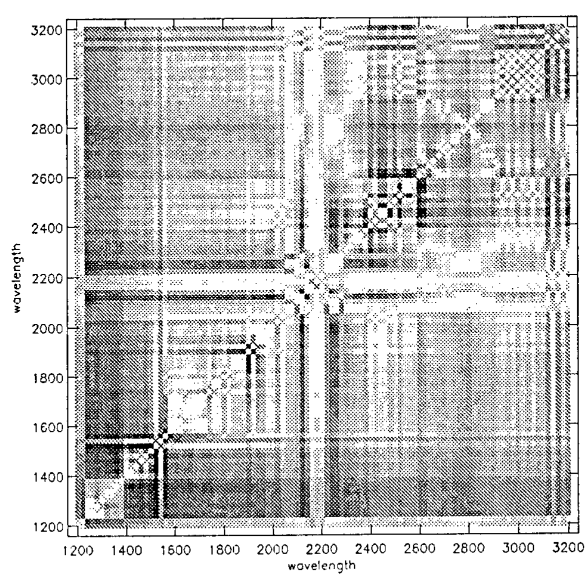

Figure 1: The absolute value of the correlation coefficients between the central depth of the 6284 DIB normalized by $E(B-V)$ and the colour excess $E(\lambda_1 - \lambda_2)/E(B-V)$. Darker shade indicates higher correlation.

One of the possible explanations for such correlation is shielding of the DIB-producing molecules from the ulraviolet light by the UV-absorbing dust. This kind of relation might be most probable when the strength of a particular DIB correlates best with the far-UV part of the extinction curve, as is the case for e.g. the 6284 DIB. Another possibility is that the DIB carriers and the particles responsible for the particular part of the extinction curve are both products of the same process - e.g. the DIB being caused by large molecules, while the extinction by small grains of similar composition. There is also a possibility that a population of grains act as catalyst or the source of material for the creation of the DIB carriers.

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Laboratory Simulations of the Interaction of Interstellar Carbon Particles with UV Photon and Atomic Hydrogen

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The 3.4 μm absorption band provides direct evidence for the presence of organic compounds in the diffuse interstellar medium. There is, however, a distinct absence of the band in the spectra of molecular cloud dust. The difference between diffuse and dense environments is enigmatic and represents a strong constraint for the identification of the band carrier material. Here we discuss experiments performed under simulated diffuse and dense interstellar medium conditions. They are aimed at studying the variations of the composition and of the optical properties of carbonaceous grains in response to UV irradiation and H atom interaction. On the basis of the laboratory results, a new model for the formation and evolution of the organic materials responsible for the 3.4 μm band is presented.

Atmospheric Extinction at the Skalnaté Pleso Observatory

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Special filters for photoelectric photometry of comets enable to study the atmospheric extinction not only in the broad band photometric systems but also in the intermediate band IHW/IAU system covering wavelengths from 365 to 514 nm, as well. Extinction coefficients, which are characteristics of an atmospheric state, are by-products of observations of bright comets. Contrary to the observations of variable stars, the comets have to be very frequently observed a few degrees above the horizon and so wide intervals of air masses are used at calculation of characteristic values.

Extinction measurements obtained during the observations of comets 1P/Halley in 1985/86, 23P/Brorsen-Metcalf in 1989 and C/Austin in 1990 are used in this study. 25 observational nights cover all the parts of year with the exception of spring with cloudy weather in our mountain site and June with the shortest observational nights. Average extinction coefficients are derived in the paper and some conclusions of common validity (in central European conditions) are formulated.

The results of IHW/IAU extinction study have been compared with results of UBV extinction coefficients gained as a by-product of photoelectric photometry of variable stars (407 nights in the interval from 1962 to 1995). Seasonal and long-term variations of atmospheric extinction are discussed.

SESSION 4

Dynamics and Applications to Systems in the Universe

Radiation Forces on Each Dipole in the Discrete Dipole Approximation

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A theory is presented that allows calculation of radiation forces on each dipole in the Discrete Dipole Approximation. An algorithm is proposed that allows efficient (i.e. in O(N log N)) calculation of the radiation forces in DDA. Finally, a possible application in the aggregation of dust particles in circumstellar disks is suggested.

Covariant Equation of Motion for Arbitrarily Shaped Dust Particle in the Field of Electromagnetic Radiation

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Covariant form of equation of motion for a particle is required if one wants to be sure that the motion of the particle is correctly described.

Relativistically covariant form of equation of motion for real particle under the action of electromagnetic radiation is derived. Various formulations of the equation of motion in the proper frame of reference of the particle are used. Equation of motion is expressed in terms of particle's optical properties, standardly used in optics for stationary particles:
i) dimensionless efficiency factors Q'_{abs}, Q'_{sca}, Q'_{ext} are used;
ii) pressure cross section 3×3 matrix is used.

Main attention is devoted to the reformulation of the equation of motion in a general frame of reference, e. g., in the frame of reference of the source of electromagnetic radiation. This is the crucial form of equation of motion in applying it to motion of particles (cosmic dust) in the Universe if electromagnetic radiation acts on the particles.

Derived covariant equation of motion represents generalization of the the well-known Poynting-Robertson effect. The obtained equation of motion yields orbital evolution which may be significantly different from orbital evolution of spherical dust particle characterized by the Poynting-Robertson effect.

The Capture of Interstellar Dust: Electromagnetic Radiation and Lorentz Force

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The capture of interstellar dust using only special form of electromagnetic radiation force (together with gravity) was discussed by Jackson [2]. It may be said that Jackson's access holds for spherical dust particles, only. However, real particles are nonspherical. The case of possible capture of interstellar dust due to electromagetic radiation force also for nonspherical particles may be found in [6].

The improvement of [6] in comparison with [2] is evident – nonspherical cosmic dust particles are considered, also. However, small interplanetary dust particles are characterized also by nonzero value of electric charge. In order to generalize the special form of interaction between cosmic dust particle and solar electromagnetic radiation, we have to take into account Lorentz force, also. The paper deals with possible capture of interstellar dust for the case that the following forces are considered, simultaneously: gravitational force of the Sun, solar electromagnetic radiation force for nonspherical particle, solar wind force for noncharged particle (radial component for solar wind velocity vector is considered), and, Lorentz force.

Equation of motion used in the numerical simulations corresponds to Eq. (27) in [5] together with addition of acceleration corresponding to Lorentz force, and solar wind effect. We consider cosmic dust particles of various radii, from 0.1 microns up to 2 microns, and, with other various optical characteristics (mass density, refractive index). Polychromatic solar radiation is considered with density function taken from [3]. The interplanetary magnetic field is approximated by Parker spiral [7] and the method of calculating Lorentz force corresponds to [1] (solar cycle and different orientations of magnetic field for northern and southern hemispheres are also considered). The value of surface electric potential is + 3 V for heliocentric distances less than 200 AU and it decreases beyond 200 AU according to [4] (moreover, it is supposed that the surface electric potential does not depend on grain size).

The results for possible capture of interstellar compact nonspherical dust particles (asphericity factor is 4/3) are compared with the analogous results for spherical ones (capture ratio).
Results for the particles of different composition (ice, enstatite, iron) and mass density are depicted in Figures 1-3; heliocentric velocity at infinity v_∞=26 km/s. Analysis of the results shows that the capture ratio for particles of (effective) radii 0.6-1.0 μm (approximately) is a decreasing function of radius for the considered material composition. Capture ratio exhibits strong dependence on material composition for radii less than 0.6 microns, and, as Figures 1-3 show, capture ration may be even more than ten (up to about 100). Particles larger than about 1.5 micron in radii, for ice and enstatite, are characterized by capture ratio value less than one, i. e., more spherical particles

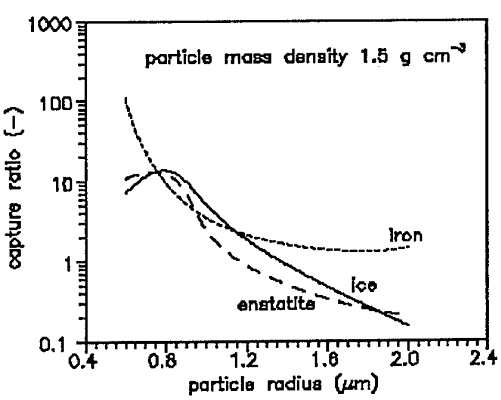

Fig. 1: *Ratio of captured nonspherical particles to spherical ones in Solar System*

are captured than nonspherical ones. Figures 1-3 yield that the radius is a decreasing function of mass density for a given capture ratio less than one.

This result is quite important for understanding of the ratio between the total influx of interstellar dust particles into Solar System and the flux of the captured dust particles.

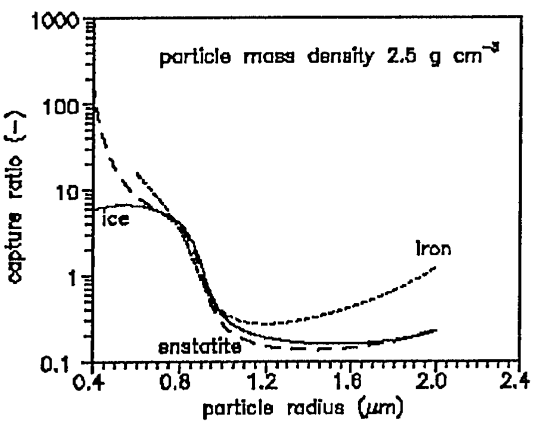

Fig. 2: *Ratio of captured nonspherical particles to spherical ones in Solar System*

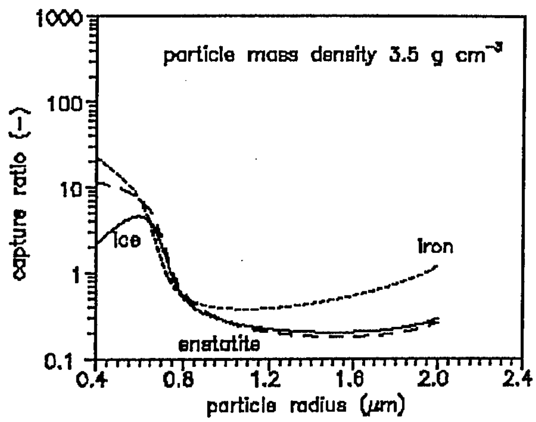

Fig. 3: *Ratio of captured nonspherical particles to spherical ones in Solar System*

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Index of Participants

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